NITROGEN EFFECTS ON LOW-PROTEIN AND SEMIDWARF GENOTYPES FOR MALTING BARLEY PRODUCTION IN WESTERN NORTH DAKOTA

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The Supervisory Committee certifies that this ***disquisition*** complies with North Dakota State University's regulations and meets the accepted standards for the degree of

MASTER OF SCIENCE

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ABSTRACT

Producing barley that meets the quality specifications set by the malting and brewing industry can be difficult in western North Dakota growing conditions. Semidwarf and low protein genotypes may help producers of malting barley meet these stringent specifications. Dryland and irrigated experiments were conducted in western North Dakota that evaluated agronomic performance and grain quality of four groups of genotypes classified by protein level and height class at four different nitrogen levels. Biomass samples were analyzed to determine if differences in nitrogen use and translocation existed between genotype groups. Low protein genotypes had less total nitrogen uptake, higher straw nitrogen content, and lower grain protein content (GPC) than their conventional protein counterparts. Increasing rates of nitrogen fertilizer increased GPC, grain yield, straw nitrogen content, and total nitrogen uptake. Semidwarf and low-protein genotypes do not have inherent grain yield or quality disadvantages compared to their conventional counterparts.

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INTRODUCTION

North Dakota consistently ranks among the top five states for US barley (*Hordeum vulgare* L.) production on an annual basis. Twenty-one percent of all US barley was produced in North Dakota between 2010 and 2014 (USDA-NASS, 5-yr avg.). Beginning in the mid to late-1990's, malting barley production shifted from the eastern and central crop reporting districts to the northwest and north central districts in North Dakota, mainly due to the high occurrence of Fusarium head blight (FHB), incited by *Fusarium graminearum* Schwabe [telomorph *Gibberella zea* (Schwein)]. During the years 1993-1997, as much as 81% of the malting barley crop produced in North Dakota, South Dakota, and Minnesota had unacceptable quality due to the accumulation of high levels of the mycotoxin deoxynivalenol (DON) produced by *F. graminearum* (Windels, 2000). Excessive levels of DON are still one of the leading causes for the rejection of malting barley by grain buyers in North Dakota (IBMS, 2007).

In 1999, more than 62 percent of the malting barley crop in North Dakota was grown in the eastern and central districts (Beard and Waldhaus, 2000). Currently, the production is concentrated in the northwest and north-central districts. These districts comprised almost one-half (45 percent) of statewide barley production in 2013 (USDA-NASS, 2014). Even though disease pressure for FHB is much lower in western North Dakota due to environmental conditions that are not favorable for disease development, other problems can limit barley acceptance for malting. These problems include excessive grain protein in dryland produced barley and lodging of barley produced under irrigation.

Barley cultivars specifically adapted for production in western North Dakota are being developed as part of the Western Malting Barley Project. Improved cultivars for dryland production will have gene(s) that reduce protein up to two percentage units as compared to

current cultivars. New cultivars for irrigated production will have the semidwarf plant height phenotype so they are less prone to lodging. In addition, lines with the combination of low-protein and semidwarf traits are being developed to determine if yields can be significantly increased under irrigation when inputs such as water and nitrogen fertilizer application are optimized. It is thought that increasing nitrogen fertilization of genotypes with the semidwarf and low-protein characters would maximize yield, without the usual consequences of excessive lodging and unacceptable grain protein under irrigated conditions. Under dryland conditions, it is thought that genotypes with the low-protein character will perform better in the western North Dakota climate and have acceptable protein despite hotter and drier growing conditions.

This experiment has four main objectives, which are: i) to determine if genotypes with the low-protein characteristic will have better agronomic performance and grain quality than current conventional protein cultivars under dryland conditions when different nitrogen fertilizer rates are applied pre-plant, ii) to determine if genotypes with the semidwarf, low-protein, or both characters combined have better agronomic performance and grain quality than current conventional height and conventional protein cultivars under irrigated conditions when different nitrogen fertilizer rates are applied pre-plant; iii) to determine if low-protein genotypes differ from conventional genotypes in regards to nitrogen translocation within the plants, and iv) to determine if low-protein genotypes differ from conventional genotypes in regards to nitrogen use efficiency (NUE), harvest index (HI), and nitrogen harvest index (NHI).

LITERATURE REVIEW

North Dakota Barley Production

As malting barley continues to move into western North Dakota, production practices need to be defined that help barley growers make informed growing decisions and increase their chances of producing malting barley that meets the specifications of maltsters. Ideally, malting barley should have protein levels between 11.5 and 13.5% for six-rowed cultivars and 11.5 and 13.0% for two-rowed cultivars. Additionally, percentage of plump kernels should be greater than 90% for two-rowed cultivars and greater than 80% for six-rowed cultivars to meet current specifications (AMBA, 2014).

Malting barley grown in western North Dakota has a higher chance of being rejected for malting than malting barley grown in eastern North Dakota due to potentially higher protein levels and higher percentages of thin kernels caused by the hotter and dryer growing conditions. According to a grower survey from 2007, the three main reasons for malting barley to be rejected by grain buyers in North Dakota are excessive DON content, excessive percentage protein, and an insufficient percentage of plump kernels. In western regions of the state, high grain protein and insufficient plump kernels were the largest factors contributing to malting barley rejection (IBMS, 2007). There are severe economic disadvantages for producers if malting barley is rejected. Rejected malting barley is either used on the farm for livestock feed or enters the feed barley market at a severe discount compared to malting barley. The average price per bushel in the years 2008-2013 was $237.46 per tonne ($5.17 per bushel) for malting barley and $180.05 per tonne ($3.92 per bushel) for feed barley. There was a $57.41 per tonne ($1.25 per bushel) average premium for malting barley versus feed barley in the marketing years 2008-2013 (USDA-NASS, 2014). According to the 2014 Projected Crop Budget for northwest North

Dakota, the estimated cost to produce malting barley with a yield of 2.8 tonnes per hectare (52 bushels per acre) is $646.05 per hectare ($261.56 per acre) (Swenson and Haugen, 2013). Using the average prices per bushel for malting and feed barley listed above, a producer could expect a projected return of $116.24 per hectare ($47.06 per acre) for malting barley or a projected loss of $39.17 per hectare ($15.86 per acre) for barley sold for feed.

Achieving acceptable protein and plump kernel levels can be difficult from year-to-year under dryland conditions. Fertilizing malting barley can be a balancing act for producers. If excessive nitrogen is applied yields may be economically feasible; however, grain protein may be unacceptable to grain buyers (Nedel, 1993). If too little nitrogen is applied, grain protein and kernel plumpness may be acceptable, but grain yields may not be economically viable. In years when the price difference between malting barley and feed barley is great, it may be more advantageous to sacrifice yield to meet malt quality specifications. Likewise, the cost of nitrogen fertilizer also affects the decision of how much nitrogen fertilizer should be applied. Nitrogen fertilizer application rates should be adjusted to ensure the optimum economic yield of both feed and malting barley (Birch and Long, 1990).

Effect of Nitrogen Fertilizer on Barley Growth

Nitrogen has been shown to affect the growth of barley in many ways and is a nutrient of major importance to malting barley production. The effect of nitrogen on barley growth has been widely studied. Multiple studies agree that increasing rates of nitrogen have a positive correlation with yield (Reisenauer and Dickson, 1961; Zubriski et al., 1970; Lauer and Partridge, 1990; Weston, 1992). Some of the responses have been quadratic or curvilinear (Eagles et al., 1995; O'Donovan et al., 2011), while others have been linear (Varvel and Severson, 1987).

Papastylainou (1995) found that grain yield response to nitrogen was quadratic at sites with low precipitation, but were linear or quadratic at sites with higher rainfall depending on year.

Yield response of malting barley to nitrogen has been shown to be dependent on cultivar (Birch and Long, 1990) and the amount of residual nitrogen available in the soil before fertilizer is applied (Zubriski et al., 1970; Lauer and Partridge, 1990).

The effect of nitrogen fertilizer on grain yield can also be impacted by late planting versus early planting (Zubriski et al., 1970, Lauer and Partridge, 1990; Weston et al. 1993). Weston (1992) found that delaying planting two weeks caused grain yields to be reduced by 1.1 Mg ha^{-1} across four North Dakota locations. Zubriski et al. (1970) observed grain yield reductions of 295 kg ha^{-1} when planting was delayed two weeks across 13 North Dakota environments, but grain yield increased with the addition of nitrogen fertilizer regardless of planting date. In addition, the effect of nitrogen fertilizer on barley grain yield can be dependent on growing season precipitation and soil moisture. Bole and Pittman (1980) conducted research on the effect of soil moisture at planting, growing season precipitation, and nitrogen level on barley yields. They observed that precipitation during the growing season had a three times greater effect on barley response to nitrogen than soil moisture at planting.

Birch and Long (1990) studied the effect of nitrogen on growth, yield, and grain protein content of barley. They measured yield components, namely number of tillers, number of fertile tillers, and the percentage of fertile tillers. The number of tillers and the number of fertile tillers increased with increases in nitrogen level; however, the percentage of fertile tillers decreased under irrigated conditions in Queensland, Australia. Baethgen et al. (1995) studied the effect of nitrogen fertilizer on growth, grain yield, and yield components of malting barley in Uruguay. They observed that tiller number increased when 100% of the nitrogen was applied at sowing

versus split application at mid-tillering (Z22) or end of tillering (Z30). The number of spikes per square meter and the number of kernels per square meter increased with increasing rates of nitrogen regardless of application timing; however, there was an increase in tillers when more nitrogen was applied at sowing versus mid-tillering. This can translate into higher grain yields when there is little or no moisture stress, but fewer fertile tillers in moisture-deficient conditions. Split application was found to increase grain yields 80 to 90 percent of the time when compared to a single application of nitrogen at sowing. The large number of tillers from early season application of nitrogen can cause fewer fertile tillers under stress conditions, as tillers compete for light and nutrients with each other. O'Donovan et al. (2011) also demonstrated that increasing levels of nitrogen application increased the number of tillers in a linear fashion, regardless of seeding rate. Number of barley plants per square meter declined with increasing nitrogen levels, but was highly variable across environments. The authors attribute the possible decline of plant density to variable organic matter levels and soil moisture levels at or during sowing. The ability to consistently maintain adequate separation between fertilizer and seed was also noted as a possible explanation.

Nitrogen fertilizer application has various other effects on barley growth. Increasing rates of nitrogen fertilizer has been shown to delay spike emergence by up to nine days depending on cultivar (Birch and Long, 1990). O'Donovan (2011) also observed a positive relationship between days to maturity and increasing nitrogen levels. Weston (1992) recorded positive association between increasing plant heights and nitrogen fertilizer rates, which can lead to taller plants that are more prone to lodging, especially in areas of high potential yield (Nedel et al., 1993). Lodging can also cause reductions in kernel weight as found by Baethgen et al.

(1995) and others. Harvest index, which is defined as grain yield divided by the total amount of above-ground biomass, also tends to decrease as nitrogen levels increase (Birch and Long, 1990).

Cultivars differ in the amount of nitrogen needed to achieve optimum yields (Lauer and Partridge, 1990). Insufficient amounts of nitrogen, especially during plant establishment, can reduce grain yield and end-use quality below acceptable levels (Lauer and Partridge, 1990; Baethgen et al., 1995).

Effect of Nitrogen Fertilizer on Barley and Malt Characteristics

The relationship between nitrogen and grain protein concentration (GPC) is well-known and researched. Reisnauer and Dickson (1961) found that barley nitrogen increased incrementally with nitrogen fertilizer application. Eagles et al. (1995) found that GPC and nitrogen fertilizer level were positively correlated, but response to nitrogen rate was markedly different in each of two years, impacted mainly by the amount of precipitation received. The season x nitrogen interaction was highly significant for GPC, indicating the importance of environmental effects on GPC. In a study conducted by Birch and Long (1990), they observed that GPC increased with increasing rates of nitrogen, and that there was a significant nitrogen rate x cultivar interaction. Nitrogen was applied in increments of 50 kg ha^{-1}, starting from 0 and increasing to 200 kg ha^{-1}. The GPC of 'Grimmet' did not increase until rates exceeded 50 kg ha^{-1}, while the GPC of 'Galleon' actually decreased when the initial 50 kg ha^{-1} rate was applied, and then increased with rates of nitrogen greater than 50 kg ha^{-1}. 'Grimmet' also had the highest number of tillers per m^2 and the greatest yield response to increasing rates of nitrogen fertilizer. This could explain why GPC decreased with the initial application rate of 50 kg ha^{-1}. 'Corvette' was found to have a positive linear response to GPC from nitrogen application. Grain protein concentrations for malting-type cultivars were still found to be in the acceptable range ($\leq$ 11.5%)

at nitrogen rates up to 200 kg ha^{-1} in irrigated conditions. By contrast, Weston (1992) found that GPC in genotypes without the low-protein trait were found to exceed levels set by grain buyers (135 g kg^{-1}) when rates higher than 100 kg ha^{-1} of nitrogen were applied under dryland conditions. Grant et al. (1991) noted a similar response of cultivars grown under high moisture conditions in the Canadian provinces of Manitoba and Saskatchewan. The authors referred to this phenomenon as the lag phase. This occurs when small amounts of nitrogen applied will produce a large increase in dry matter production, but grain and straw nitrogen concentration do not increase.

End-use quality characteristics of barley grain can be significantly affected by nitrogen application, especially in environments with moisture stress later in the growing season. Weston et al. (1993) found that increasing levels of nitrogen up to 100 kg ha^{-1} decreased kernel plumpness and kernel weight across locations; however, no further decreases were observed for rates above 100 kg ha^{-1}. O'Donovan et al. (2011) observed similar reductions in kernel weight and diameter with increasing nitrogen levels on two commonly grown Canadian malting barley cultivars, AC Metcalfe and CDC Copeland. The reduction in kernel weight was more pronounced in CDC Copeland than AC Metcalfe. Reisnauer and Dickson (1961) and Fathi et al. (1997) found decreases in kernel weight with increasing levels of nitrogen and that kernel weights were lowest at the highest yield levels. Papastylianou (1995) obtained similar results, indicating that kernel weight, as well as volume weight decreased with increasing nitrogen levels, but was cultivar dependent.

Others have reported mixed results due to increasing nitrogen levels on kernel plumpness (Zubriski et al., 1970) or kernel weight (Baethgen et al., 1995), which are most likely due to

environment or environment x cultivar interactions (Eagles et al., 1995). Birch and Long (1990) reported significant increases in kernel weight with nitrogen application in irrigated conditions.

Nitrogen and grain protein concentration are known to have multiple effects on malting characteristics of barley. Pomeranz et al. (1976) concluded that GPC was correlated with almost all of the malt parameters that were studied with the exception of diastatic power (DP) and wort color. Increasing levels of nitrogen fertilizer increased GPC and DP, and decreased fine grind extract. Similar results were obtained by Edney et al. (2012) when comparing nitrogen fertilizer rates, seeding rates, and cultivar effects on barley and malt quality. Increasing levels of nitrogen resulted in decreased endosperm modification as indicated by the friability and Calcofluor methods. Additionally, malt extract levels decreased with increasing nitrogen application, while DP and α-amylase levels increased. Kolbach index (or the measure of the ratio of soluble protein to total grain protein) decreased as nitrogen rate increased. The relationship between germinative energy and nitrogen application rate appeared to be curvilinear. Germinative energy increased with nitrogen rates up to 60 kg ha^{-1}, but decreased at nitrogen rates higher than 90 kg ha^{-1}. As observed with agronomic factors, the relationship between GPC, malt characteristics, and nitrogen fertilizer was affected by cultivar and environmental effects, including available moisture and temperature. The increases in DP and α-amylase, which are measures of enzyme activity, are not surprising because enzymes are proteins.

Eagles et al. (1995) studied the effects of cultivar, nitrogen fertilizer rate, and environmental effects on malt quality. The response of GPC, diastatic power (DP), and malt extract was highly correlated to the rate of nitrogen fertilizer applied. The relationship was stronger in an environment with warmer temperatures and less precipitation than in an environment with cooler temperatures and more precipitation. Diastatic power was increased

with the addition of nitrogen fertilizer; however, an increase in grain protein and a decrease of malt extract was also observed, both of which are negative consequences. Increasing nitrogen fertilizer rate also caused increased wort protein and α-amylase activity (Weston, 1993). α-amylase activity is one of many enzyme components comprising DP. ß-amylase is the largest contributor to DP; however, the activity of this enzyme per se is not a typical measurement of malt quality. Nedel et al. (1993) found a significant genotype x nitrogen interactions for soluble protein, soluble to total protein ratio (S/T), wort viscosity, and α-amylase.

Low-Protein Barley Genotypes

The source of the low-protein trait incorporated into genotypes used in this experiment traces back to the cultivar Karl, which was developed cooperatively by the United States Department of Agriculture-Agricultural Research Service and the Idaho Agricultural Experiment Station in 1974 (Wesenberg et al., 1976). Karl has a unique low-protein character as compared to other North American malting barley cultivars. The pedigree of Karl is 'Traill'//CIho 7147/Traill. CIho 7147 was selected from a cross of 'Good Delta' and 'Everest' and was the only parent to possess the low-protein character similar to Karl (Burger et al., 1979). Burger et al. (1979) examined the protein content of Karl and related lines. Karl and other barley lines similar to Karl had lower overall GPC and hordein content than other malting barley lines tested. At the time of their publication, breeding programs in Aberdeen, Idaho and St. Paul, Minnesota developed crosses using Karl and its sister selections and found that the low-protein trait seemed highly heritable. Goblirsch et al. (1996) obtained similar results. In more recent research, the low-protein from Karl was mapped to the centromeric region of chromosome 6H (See et al., 2002). Lines carrying the Karl allele were on average 1.3% lower in GPC than those carrying the allele from 'Lewis' in a population developed by See et al. (2002).

Genotypes genetically lower in GPC could potentially assist barley growers in meeting stringent malting barley quality standards in the warmer and drier climate of western North Dakota. Genotypes with inherently low GPC have been shown to maintain their low-protein over those genotypes with high GPC at various levels of nitrogen application (Weston et al., 1993; Emebiri and Moody, 2004). Weston et al. (1993) found that low-protein genotypes possessed grain protein levels that were within the limits set by maltsters and brewers at nitrogen rates up to 200 kg ha^{-1}. Conventional protein genotypes exceeded the grain protein limit when fertilized with the high rates of nitrogen. However, low-protein genotypes tended to have fewer plump kernels (Emebiri and Moody, 2004; Weston et al., 1993) and lower kernel weights (Weston et al., 1993) than their high-protein counterparts when rates of nitrogen fertilizer were increased. However, the low-protein cultivars Rawson, Pinnacle, and ND Genesis developed and released by NDSU have similar kernel plumpness as conventional-protein cultivars. Additionally, Rawson has higher kernel weight than conventional-protein cultivars (Franckowiak et. al, 2007).

According to Goblirsch et al. (1996), breeding commercially acceptable, low-protein cultivars has been difficult although Karl had been used widely in the breeding program at North Dakota State University. Low-protein barleys related to Karl typically had darker kernel color and lower DP than conventional-protein cultivars. These traits could make barley produced from low-protein lines undesirable for malt production. Dark kernel color has traditionally been used by buyers to indicate grain that is weathered or has some degree of microbial infection, which is undesirable in the malthouse. DP is a measure of the enzymatic activity of the malt itself, and is mainly composed of β-amylase. This enzyme breaks down complex starches to maltose, which can be more easily fermented. Brewers that use adjuncts such as corn (*Zea mays* L.) or rice

(*Oryza sativa* L.) during brewing generally desire higher levels of DP because the adjunct does not provide any enzymes. Brewers that produce all-malt beers don't require as high of levels of DP; thus, the lower DP of the low-protein lines may be sufficient for brewing of all-malt beers. Goblirsch et al. (1996) found that the low-protein character is not highly correlated to either DP (<0.32) or kernel color (<-0.23), indicating that it should be possible to develop cultivars with acceptable grain quality and the low-protein trait. Pinnacle is an example of a recently released (2007) two-rowed barley cultivar developed by North Dakota State University with the low-protein trait, and acceptable malt quality profile.

Semidwarf Barley Cultivars

Lodging can be a serious problem in an irrigated production system, causing some yield loss of standard height barley cultivars. Semidwarf cultivars may be a suitable solution to the problem of lodging under irrigated conditions. By increasing lodging resistance, cultivars can more efficiently use higher levels of nitrogen and water (Nedel et al., 1993). The use of semidwarf cultivars in barley breeding programs is increasing in popularity because of their increased standability and yield, especially under irrigation (Fathi et al., 1997) and is a common characteristic of cultivars developed in western Europe. Nedel et al. (1993) compared semidwarf isotypes of barley cultivars Morex, Hazen, Norbert, and Andre with their standard height counterparts at various rates of nitrogen fertilizer. Although grain yield and quality of the semidwarf isotypes was not as high as the named cultivars in this study, malt quality was generally higher in the two-rowed semidwarf isotypes than their two-rowed standard height counterparts. The authors attributed the lack of agronomic performance to the fact that the isotypes were raw induced mutants and not improved by crossing. A study conducted by Fathi et al. (1997) determined that the semidwarf two-rowed barley cultivar Skiff had the greatest yield

response to nitrogen when compared to other commonly grown standard height malting barley cultivars in Australia. Grant et al. (1991) studied the effect of nitrogen fertilizer rate on yield of semidwarf and short-strawed barley cultivars compared to standard height cultivars under varying moisture conditions. Cultivars did not differ in their yield response to different rates of nitrogen under low or moderate moisture conditions. However, under high moisture conditions, the standard height malting cultivar Bonanza had a lower yield response to nitrogen than the other feed barley cultivars. The maximum yield of Bonanza was attained at lower levels of nitrogen than the other cultivars in the trial. In contrast, the standard height, semidwarf, and short feed barley cultivars had increasing yield responses at the highest rates of nitrogen fertilizer application. Semidwarf and conventional height cultivars had similar yield responses to increasing rates of nitrogen fertilizer under the high moisture regime. The short-strawed cultivar Heartland showed the greatest yield response to increasing rates of nitrogen under the high moisture regime. Nitrogen application rates above 150 kg ha^{-1} and as high as 200 kg ha^{-1} may be justified for both malting and feed barley under fully irrigated conditions of Queensland, Australia (Birch and Long, 1990). Thus, as new cultivars are released, research should be done to determine how nitrogen fertilizer recommendations could be adjusted for different types of cultivars under high moisture conditions to maximize nitrogen use efficiency and grain yield.

Nitrogen Use Efficiency and Translocation

Nitrogen fertilizer is one of the most important and costly inputs in barley production. In recent years, increased emphasis has been placed on breeding cereal cultivars that are efficient in nitrogen use. Raun and Johnson (1999) estimated the cumulative nitrogen use efficiency (NUE) of worldwide cereal production to be only 33 percent. Le Gouis et al. (1999) noted that nitrogen is responsible for most of the phreatic water pollution caused by high-input, non-

sustainable management systems. The authors conclude that this will likely cause demand for cultivars that are low-input and environmentally-friendly by having high nitrogen uptake and leaving little residual nitrogen in the soil at harvest to maximize grain yield. Although nitrogen can be lost to leaching, surface runoff, and denitrification, plant improvement can be one of the strategies used to increase NUE in cereals. Anbessa et al. (2009) found that there are differences in NUE among spring barley cultivars, and that variation among barley genotypes can be utilized to select cultivars. As an overall trend, barley genotypes with the highest yield per unit nitrogen, were superior in NUE to genotypes with overall lower yield and performance. The author suggests that breeders could increase NUE in cultivars by utilizing evaluation under low nitrogen conditions.

Cultivars that use nitrogen efficiently may be important to enhance the profitability of malting barley under both dryland and irrigated conditions. Nitrogen use efficiency in barley cultivars differs as moisture conditions change. The feed barley cultivar Virden had higher NUE than other cultivars under low moisture conditions, while the cultivar Duke had higher NUE than other cultivars under high moisture conditions (Grant et al., 1991). This is similar to the results obtained by Przulj and Momcilovic (2001) and Fathi et al. (1997). Grant et al. (1991) determined that NUE decreases as nitrogen levels increase, especially under low moisture conditions. Grain protein concentration, straw nitrogen concentration, protein yield, and total nitrogen uptake all increased as nitrogen levels increased. The only difference observed between cultivars at various nitrogen levels was for GPC.

In a greenhouse study, Fathi et al. (1997) determined that under periods of post-anthesis stress, nitrogen is remobilized from the tillers to assist with grain filling. Grain protein concentration was more negatively affected under high rates of nitrogen than at low rates of

nitrogen when post-anthesis stress occurred. Main stem kernels had higher GPC than those of tiller kernels at the high rate of nitrogen because nitrogen was remobilized from tillers to the main stem under periods of stress. Overall, kernels derived from tillers had lower kernel weight and grain yield than kernels grown on the main stem. Cultivars responded differently when post-anthesis moisture stress and high rates of nitrogen were applied. Reductions in grain yield and kernel weight from tillers were noted in 'Stirling', 'Chebec', and 'Skiff'. Grain yield and kernel weight from tillers in 'Clipper' was minimally affected by high nitrogen levels and post-anthesis moisture stress.

Przulj and Momcilovic (2001) found that there were genotypic and environmental differences in nitrogen retranslocation to the kernel and accumulation in the kernel, and that post-anthesis nitrogen uptake is positively correlated with GPC. The cultivar x year interaction had significant effects on NHI and nitrogen retranslocation to the kernel. Nitrogen harvest index is determined by dividing grain nitrogen content by total nitrogen content of the plant in above ground parts. The ratio of translocated nitrogen to grain nitrogen is an indicator of growing conditions during the year. A low ratio would indicate poor conditions pre-anthesis, while a high ratio would indicate good growing conditions throughout the growing season. A medium ratio indicates fluctuations from the average precipitation and temperature. The authors also suggest using straw nitrogen concentration as a time and labor-saving method of determining NUE in a barley breeding program. There were significant correlations between straw nitrogen concentration and nitrogen translocation, and between straw concentration and nitrogen translocation efficiency. In addition, straw nitrogen concentration data is easier to gather than NHI, making it conducive for use in a barley breeding program to determine NUE. These results conflict with those from Bulman and Smith (1994), who concluded that post-heading nitrogen

uptake was not correlated with GPC. They found that while accumulation of nitrogen after awn emergence determined total plant nitrogen and grain nitrogen content, it had little impact on the final partitioning of nitrogen within the plant or proportion of nitrogen in the grain. They speculate that nitrogen uptake after heading occurs concurrently with carbohydrate accumulation in the grain, thereby diluting the GPC.

Limited research has been conducted on translocation of nitrogen in low-protein barley genotypes. Erickson et al. (1982) studied the feed value of barley straw from various barley genotypes, including Karl, which is a low-protein malting barley cultivar. In data collected from the Mississippi Valley Barley Nursery grown in Langdon, North Dakota in 1977, barley straw from Karl had higher potential feeding values than all other genotypes tested. Straw protein values in Karl were three percentage points higher than the next highest genotype. In a trial grown at four North Dakota locations in 1979, commonly grown malting cultivars Larker, Beacon, Glenn, Morex, and Karl were compared for straw protein content and feed value. The straw protein contents were 6.7, 6.4, 6.2, 6.6, and 8.7 percent, respectively. While grain protein was measured, it was not presented and correlations between grain protein and straw protein content were not significant. The authors suggest that the low GPC of Karl, coupled with the high straw protein values, indicate that Karl does not translocate protein to the grain as readily as other barley genotypes that are bred for malting quality.

MATERIALS AND METHODS

An experiment was conducted to determine the effects of increasing nitrogen fertilizer rates on semidwarf and low-protein genotypes and their conventional height and conventional protein counterparts at four dryland and two irrigated locations in western North Dakota.

Research sites were selected based on residual soil nitrogen level, which ranged from 16 to 78 kg ha^{-1} NO_3-N in the top 60 cm of soil at all locations (Table 1). The soil type at the Minot site is classified as a Williams loam, which is described as a fine-loamy, mixed, superactive, frigid, typic Argiustoll. The Williston soil type is classified as a Williams-Bowbells loam complex. Bowbells is described as a fine-loamy, mixed, superactive, frigid, Pachic Argiustoll. The soil type at the Richardton environment is categorized as a Daglum-Rhodes silt-loam complex. The Daglum series is described as being a fine, smectitic, frigid, Vertic Natrustoll. Rhoades is a fine, smectitic, frigid, Leptic Vertic Natrustoll. The irrigated site at Nesson Valley is classified as Lihen loamy fine sand. The Lihen series is described as a sandy, mixed, frigid, Entic Haplustoll (USDA-NRCS).

Table 1. Descriptions of locations by year and production regimen with previous crop information and NO^3-N levels in the top 0-60 cm of soil.

Production regimen	Year	Location	Previous crop	Initial Soil NO_3-N (kg ha^{-1}) 0-15 cm	16-60 cm	0-60 cm
Dryland	2005	Minot	Edible bean	19	57	76
		Williston	Spring wheat	10	9	19
	2006	Richardton	Oat	8	63	71
		Williston	Spring wheat	4	12	16
Irrigated	2006	Nesson Valley	Potato	33	45	78
	2007	Nesson Valley	Sugarbeet	25	30	55

Treatments were assigned to experimental units using a randomized complete block design (RCBD) with a split block arrangement. One group of whole plots included four rates of

nitrogen: 0, 50, 100, and 150 kg N ha^{-1} at irrigated sites; and 0, 25, 50, and 75 kg N ha^{-1} at dryland sites. The perpendicular whole plots consist of 25 six-rowed and two-rowed barley genotypes (Table 2). Each treatment combination (genotype x N rate) was replicated three times within a site.

Twenty-five barley genotypes were assigned to one of four groups based on grain protein concentration (GPC) and plant height. Groups were created that contained at least six genotypes, of which at least one was a two-rowed genotype. The first group included commonly grown genotypes with conventional protein level and conventional height. This group consisted of the cultivars Robust, Lacey, Drummond, Tradition, Stellar-ND, Legacy, and Conlon. These genotypes currently are or were six-rowed and two-rowed barley cultivars recommended for malting according to the American Malting Barley Association (AMBA, 2009).

The remaining groups of genotypes included experimental breeding lines from the barley-breeding program at North Dakota State University. These genotypes were chosen based on preliminary (first-year) yield trial and protein data that indicated their suitability for this experiment. Height and protein data were used to classify each of these genotypes into the remaining three groups. The second group contained genotypes that possessed the conventional height and low-protein characters, the third group was comprised of genotypes with the semidwarf height and the conventional protein characters, and the fourth group included genotypes with both the semidwarf and low-protein characters. After this experiment was conducted, however, some of the genotypes were reclassified to more accurately represent their respective protein grouping. The following table (Table 2) lists the initial classification of the genotypes, as well as the reclassification of the experimental genotypes into the appropriate genotype groups.

Table 2. Spring barley genotypes evaluated in this study and their classification by height and protein.

Genotype	Row-type	Height class	Revised protein class	Initial protein class
Conlon	Two-rowed	Conventional	Conventional	Conventional
Drummond	Six-rowed	Conventional	Conventional	Conventional
Lacey	Six-rowed	Conventional	Conventional	Conventional
Legacy	Six-rowed	Conventional	Conventional	Conventional
Robust	Six-rowed	Conventional	Conventional	Conventional
Stellar-ND	Six-rowed	Conventional	Conventional	Conventional
Tradition	Six-rowed	Conventional	Conventional	Conventional
2ND20798	Two-rowed	Conventional	Conventional	Low
ND23302	Six-rowed	Conventional	Conventional	Low
ND23309	Six-rowed	Conventional	Conventional	Low
ND23283	Six-rowed	Conventional	Low	Low
ND23288	Six-rowed	Conventional	Low	Low
ND23305	Six-rowed	Conventional	Low	Low
2ND22170	Two-rowed	Semidwarf	Low	Conventional
ND23286	Six-rowed	Semidwarf	Conventional	Conventional
ND24614	Six-rowed	Semidwarf	Conventional	Conventional
ND24615	Six-rowed	Semidwarf	Conventional	Conventional
ND24616	Six-rowed	Semidwarf	Conventional	Conventional
ND24617	Six-rowed	Semidwarf	Conventional	Conventional
2ND22182	Two-rowed	Semidwarf	Low	Low
ND23285	Six-rowed	Semidwarf	Conventional	Low
ND23300	Six-rowed	Semidwarf	Conventional	Low
ND23303	Six-rowed	Semidwarf	Conventional	Low
ND23304	Six-rowed	Semidwarf	Conventional	Low
ND23310	Six-rowed	Semidwarf	Conventional	Low

Dryland sites were cultivated in the spring before nitrogen fertilizer was applied. Nitrogen fertilizer was applied pre-plant using a Gandy 6500 Series drop spreader (Gandy Co.; Owatonna, MN) perpendicular to the planted row direction. The spreader was 1.83 m wide, so two passes were needed to fertilize the center 3.66 m of the original 3.96 m plot length. Nitrogen was applied on dryland sites using a commercial calcium nitrate ($Ca(NO_3)_2$) fertilizer with the analysis of 15.5-0-0. Urea ($CO(NH_2)_2$) fertilizer with an analysis of 46-0-0 was used at the irrigated sites. The urea was incorporated after application using a small cultivator or rototiller

to lightly mix the fertilizer into the soil in an effort to minimize volatilization of nitrogen (NH_3) into the atmosphere.

After fertilizer treatments were applied, plots were seeded using an ALMACO small plot grain drill (ALMACO; Nevada, IA). At dryland locations, a grain drill with seven rows spaced 17.8 cm apart was used. At irrigated locations, a grain drill with three rows spaced 30.5 cm apart was used. Dryland plots were seeded at the rate of 2.22 million pure live seeds ha^{-1}. For irrigated sites, plots were seeded at the rate of 3.71 million pure live seeds ha^{-1}. All locations were sown within the desirable planting dates for spring barley in North Dakota (Table 3). After sowing, plot length was shortened to 2.44 m. Final plot dimensions were 2.44 m x 1.52 m (3.71 m^2) at dryland locations and 2.44 m x 1.07 m (2.61 m^2) at irrigated locations.

Agronomic trait data collected at all location years include heading date and plant height. Differential lodging and stem breakage were noted at Minot in 2005 and Richardton in 2006. There was no differential lodging or stem breakage noted at the other locations. Heading date was recorded number of days after 31 May when 50% of the spikes in a plot were 50% emerged from the boot. Plant height was noted as distance from ground level to the top of the spike (excluding awns) recorded in centimeters. Lodging was scored using a 1 to 9 scale with 1 being no lodging and 9 being completely flat. Stem breakage was scored using a 1 to 5 scale immediately prior to combining, with a 1 being no stem breakage and a 5 being completely broken down.

When plants were physiologically mature (Zadoks 89), biomass samples were collected from each plot. Plants having peduncles that had lost their green color were deemed physiologically mature. One-meter length of row was collected from every plot. Biomass samples were cut one centimeter above ground level using a battery-powered, handheld lawn

shear (American Gardener; Duluth, GA). Cut samples were placed in extra heavy-duty paper bags and dried for 3 days at 38 °C. After samples were dried, spikes were separated from straw and leaf biomass. Once separated, both biomass portions were weighed separately and recorded. Protein on the spike portion of the biomass was determined using an Infratec 1241 near- infrared (NIR) analyzer (Foss North America; Eden Prairie, MN). Protein content was divided by 6.25 to provide an estimate the percentage of nitrogen from spikes (ASBC, 2009). Leaf and straw biomass was ground using a Thomas Model 4 Wiley Mill (Thomas Scientific, Swedesburo, NJ) with a 1.0 mm sieve. This fraction was ground and analyzed for nitrogen content using the Kjeldahl method (AOAC, 2012).

Several biomass traits were recorded to help determine how low-protein genotypes differed from conventional-protein genotypes. Percent straw protein and percent grain protein were measured, as well as straw nitrogen yield, grain nitrogen yield, harvest index (HI), nitrogen harvest index (NHI), total nitrogen uptake, and nitrogen use efficiency. Straw nitrogen yield was calculated by multiplying straw weight by the percent of straw nitrogen, and reported in kg ha^{-1}. Grain nitrogen yield was calculated by multiplying the weight of head biomass and the percent of grain nitrogen, and reported in kg ha^{-1}. Harvest index was calculated by dividing the weight of head biomass by the dry weight of all plant biomass at maturity. Nitrogen harvest index was calculated by dividing the grain nitrogen yield by the sum of grain nitrogen yield and straw nitrogen yield. The sum of grain nitrogen yield and straw nitrogen yield is known as total nitrogen uptake. Nitrogen harvest index was used to compare low-protein and conventional protein genotypes for differences in nitrogen translocation. Nitrogen use efficiency was calculated using the equation described by Grant et. al, 1991:

Nitrogen Use Efficiency = 100 x ((Total Nitrogen Uptake with Nitrogen – Total Nitrogen Uptake with no Nitrogen) / Nitrogen Fertilizer Rate)

After biomass samples were removed, the plot areas were reduced to 3.49 m^2 and 2.25 m^2 for dryland and irrigated plots, respectively. The dryland plots were harvested with a Wintersteiger Classic plot combine (Wintersteiger North America; Salt Lake City, UT) at Minot in 2005 and Williston in 2005 and 2006. Dryland plots at Richardton in 2006 and irrigated plots at Nesson Valley in 2006 and 2007 were harvested with a Massey Ferguson 8XP plot combine (Kincaid; Haven, KS). All locations were harvested during the usual harvest dates for spring barley in North Dakota (Table 3). Grain samples were collected and dried to 13% moisture. Samples were then cleaned using a model SLN grain sample cleaner (A/S Rationel Kornservice; Esbjerg, Denmark). Cleaned grain samples were weighed, and grain yield was calculated.

Table 3. Planting and harvest dates by environment compared to the twenty-year historical estimate (USDA-NASS, 2010).

Environment	Planting date	Harvest date
2005 Minot	April 19	July 26
2005 Williston	May 5	August 5
2006 Richardton	May 5	August 9
2006 Williston	April 28	July 27
2006 Nesson Valley	May 4	August 8
2007 Nesson Valley	April 27	August 8
USDA-NASS North Dakota 20-year historical estimate	April 19 – June 3	July 28 – Sept 16

Barley quality traits were determined using cleaned grain samples. Quality traits included grain protein, grain color, test weight, percent plump kernels, percent thin kernels, and thousand-kernel weight. Grain protein and grain color data were collected with an Infratec 1241 near-infrared reflectance (NIR) analyzer (Foss North America; Eden Prairie, MN). Grain protein was measured as a percentage on dry matter basis. Grain color was recorded in °Lovibond or the

L- value. A higher score indicates a brighter grain color, while a lower score equates to a poor grain color. Test weight was measured using a USDA test weight apparatus (USDA, 1996) and recorded in kg hl^{-1}. Percent plump kernels and percent thin kernels were determined by using a Sortimat (Pfeuffer GmbH; Kitzingen, Germany) machine. A 100 g sample was sorted by the Sortimat machine for 2 min. Percent plump kernels are defined as the percentage of kernels retained on top of a screen with an opening 0.24 cm wide and 1.25 cm long. Percent thin kernels are defined as the percentage of kernels that pass through a screen with an opening 0.2 cm wide and 1.25 cm long. To determine thousand-kernel weights, one-thousand kernels were counted using a seed counter (Seedburo Equipment Co.; Chicago, Il.) and the subsequent weights were recorded in grams.

Data were analyzed using the analysis of variance method (PROC ANOVA) using SAS for Windows version 9.2 (SAS; Cary, NC). Height classes, protein classes, and nitrogen levels were considered fixed effects in all analyses. In the combined analyses environment was considered a random effect. The variances from individual location analyses will be considered homogeneous and combined analyses will be done if the differences between the largest and smallest Mean Squared Errors (MSE) values from individual locations experiments differ by less than a factor of ten. F-tests will be considered significant at the $P \leq 0.05$ level. Because of some instances of missing data, the LSMEANS statement was used to calculate least squared means. The pdiff option was used for means separation. Means were considered significantly different at the $P \leq 0.05$ level. Genotypes were compared by various groupings. To accomplish this, the genotype source of variation was divided into single degree of freedom comparisons. The first comparison involved grouping genotypes by height class alone (semi-dwarf vs. conventional height). The second comparison grouped the genotypes by protein class only (low-protein vs.

conventional protein). Finally the interaction of the height class and the protein class (semi-dwarf, low-protein; semi-dwarf, conventional protein; conventional height, low-protein; and conventional height, conventional protein) were compared.

RESULTS AND DISCUSSION

A randomized complete block design with a split plot arrangement was used for this experiment, which allowed for efficient application of the nitrogen treatments prior to sowing. Nitrogen application methods varied between dryland and irrigated locations. In dryland locations, commercial calcium nitrate ($Ca(NO_3)_2$) fertilizer with the analysis of 15.5-0-0 was applied. Because calcium nitrate fertilizer is not as volatile as urea, it was not incorporated into the soil in an effort to conserve soil moisture under dryland conditions. Urea ($CO(NH_2)_2$) fertilizer with an analysis of 46-0-0 was used at the irrigated sites so the higher rates of nitrogen application could be more accurately applied using the Gandy spreader (Owatonna, MN). After spreading, the urea was incorporated into the top 8-10 cm using a tractor-mounted roto-tiller in an effort to prevent nitrogen loss into the atmosphere.

Temperatures differed by less than 4.1° at all dryland and irrigated locations when compared to the thirty-year average (Table A1). 2006 Richardton had the highest temperatures among the dryland locations when compared the thirty-year average. Precipitation at the 2005 Minot location was much higher than the thirty-year average in June, while precipitation levels at the 2006 Richardton and 2006 Williston locations were well below the thirty-year average.

When plants were physiologically mature (Zadoks 89), biomass samples were collected from each plot. Plants having peduncles that had lost their green color were deemed physiologically mature. Physiological maturity in small grain crops is also known to be the point of maximum dry matter accumulation in grain. The loss of green color from the peduncle has been found to be the most accurate and easiest method of determining physiological maturity of barley in field conditions (Copeland and Crookston, 1985).

Genotypes were divided into four height and protein groups based on the results of a preliminary (first-year) yield trial. The groups were 1) conventional height – conventional protein, 2) conventional height – low-protein, 3) semidwarf – conventional protein, and 4) semidwarf – low-protein. After the experiments were conducted for the present study, the genotypes were reclassified once again to more accurately assign them to the proper groups. This reclassification had no impact on how genotypes were assigned to experimental units. The newly reclassified groups contained varying numbers of genotypes, with some of the groups having only six-rowed or two-rowed genotypes (Table 4). Only the conventional height - conventional protein group included both two and six-rowed genotypes. Test weight, thousand-kernel weight, and percentage plump kernels are traits confounded with row type because of the morphology of the spikes. Two-rowed genotypes generally have higher test weights, 1000-kernel weights, and percentages of plump kernels than six-rowed spikes. To alleviate the confounding effects of row-type on these traits, I decided not to include discussion of them.

Table 4. Number of genotypes in each group after reclassification by protein level.

Height class	Protein class	Number of genotypes	Number of six-rowed genotypes	Number of two-rowed genotypes
Conventional	Conventional	10	8	2
Conventional	Low	3	3	0
Semidwarf	Conventional	10	10	0
Semidwarf	Low	2	0	2

Nitrogen use efficiency (NUE) was calculated, but the values obtained were deemed not to be accurate enough for discussion. This is most likely due to the fact that straw nitrogen content and grain nitrogen content were measured using different methods. Straw nitrogen concentration was determined using a variation of the Kjeldahl method, which is a direct measurement of nitrogen. Grain nitrogen was determined using a near-infrared (NIR) analyzer, with the results of grain protein concentration determined by dividing the grain N amount by a

constant of 6.25 (ASBC, 2009). The differences in measurements resulted in NUE estimates that differed greatly from those found in the literature.

Only traits with meaningful and significant differences will be discussed. Significant interactions will be discussed before significant main effects. Significant three-way interactions will not be discussed due to the difficulty of interpreting results.

Dryland Experiment

Plant height

Conventional height genotypes were significantly ($P \leq 0.01$) taller than semidwarf genotypes when averaged across protein classes. Plant height for the conventional and semidwarf height classes were 56.1 and 50.4 cm, respectively. A highly significant ($P \leq 0.01$) environment x nitrogen interaction was detected for plant height (Table 5). Plant heights tended to increase as nitrogen levels increased in the 2005 and 2006 Williston experiments. The same trend for plant height was not observed in the 2005 Minot and 2006 Richardton experiments. Plant height at these locations only varied by 1.6 and 1.8 cm, respectively, over the four rates of nitrogen fertilizer. The small difference in plant height may be due to higher initial amounts of nitrogen present in the top 60 cm of soil in the 2005 Minot and 2006 Richardton environments (Table 2). Weston (1992) found that increasing rates of nitrogen caused significant increases in plant height in dryland experiments conducted in eastern North Dakota.

Table 5. Mean plant height combined across all height and protein classes arranged by nitrogen level (kg ha^{-1}) and environment.

	Nitrogen level			
Environment	0	25	50	75
	----------cm----------			
2005 Minot	64.4 f†	63.4 f	64.3 f	65.0 f
2005 Williston	48.1 b	51.4 c	53.8 d	58.6 e
2006 Richardton	45.0 a	45.8 a	44.0 a	44.3 a
2006 Williston	45.6 a	50.6 c	53.4 d	54.3 d

†Means in the table followed by the same letter are not significantly different ($P \leq 0.05$) as determined using *t*-tests between each pair of treatments.

Days to heading

The environment x nitrogen interaction was highly significant ($P \leq 0.01$) for heading date. Addition of nitrogen fertilizer tended to hasten heading in the 2005 Williston and 2006 Williston experiments, where initial soil nitrogen levels were less than 20 kg ha^{-1}. This trend was not observed in the 2005 Minot and 2006 Richardton experiments, where nitrogen fertilizer rate did not affect heading date significantly (Figure 1). This is most likely due to the fact that initial nitrogen levels in the top 60 cm of soil at these environments were relatively high; 76 and 71 kg ha^{-1}, respectively. Weston (1992) found that as nitrogen levels increased, days to heading significantly decreased.

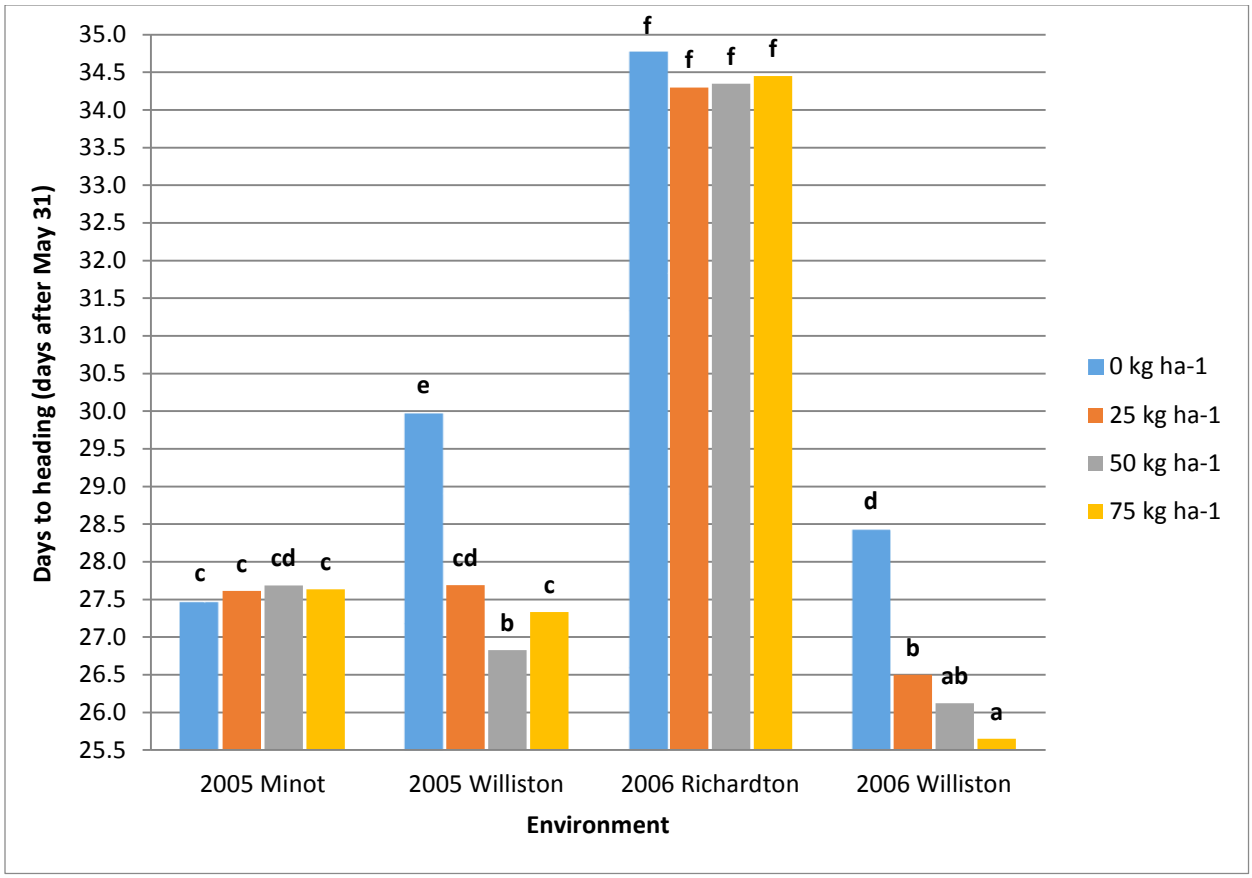

Figure 1. Days to heading (days after May 31) combined across protein and height class, arranged by environment and nitrogen level. Throughout the figure, bars topped by the same letter are not significantly different ($P \leq 0.05$).

Grain yield

No significant differences in grain yield were detected for the height class, protein class, and height x protein class sources of variation. Semidwarf genotypes performed as well as conventional genotypes in regards to grain yield. Likewise, low protein genotypes yielded similarly to conventional protein genotypes. In addition, all height and protein class combinations yielded similar to each other. These results are reassuring, as none of the height or protein genes incorporated into the lines utilized in this study appear to have a detrimental effect on yield.

The amount of nitrogen fertilizer added had a significant ($P \leq 0.05$) effect on grain yield. Grain yield increased as nitrogen levels increased, regardless of genotype. The grain yield of the 0 kg ha^{-1} nitrogen treatment was significantly less than the grain yields of the 50 and 75 kg ha^{-1} nitrogen treatments (Figure 2). Grain yield has been extensively researched and is known to increase with the addition of nitrogen fertilizer (Lauer and Partridge, 1990; Weston et al., 1993; Emebiri and Moody, 2004; O'Donovan, 2011). Grain yield was found to be positively associated with nitrogen rate, having an r^2 value of 0.85. Grain yield increased 5 kg ha^{-1} with the addition of each kg ha^{-1} nitrogen fertilizer (Figure 3).

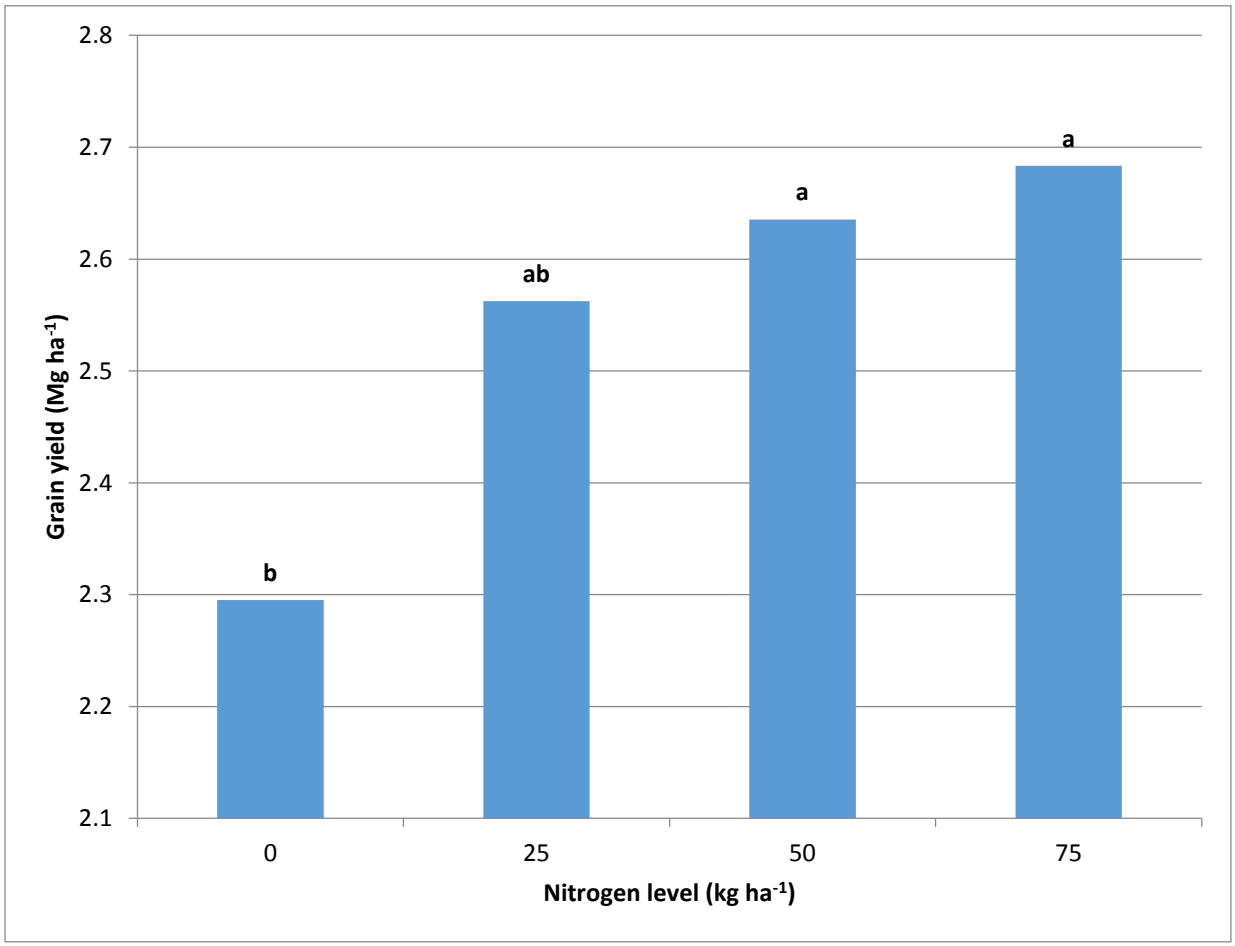

Figure 2. Grain yield (Mg ha^{-1}) combined across height classes, protein classes, and four dryland environments arranged by nitrogen level. Bars topped by the same letter are not significantly different ($P \leq 0.05$).

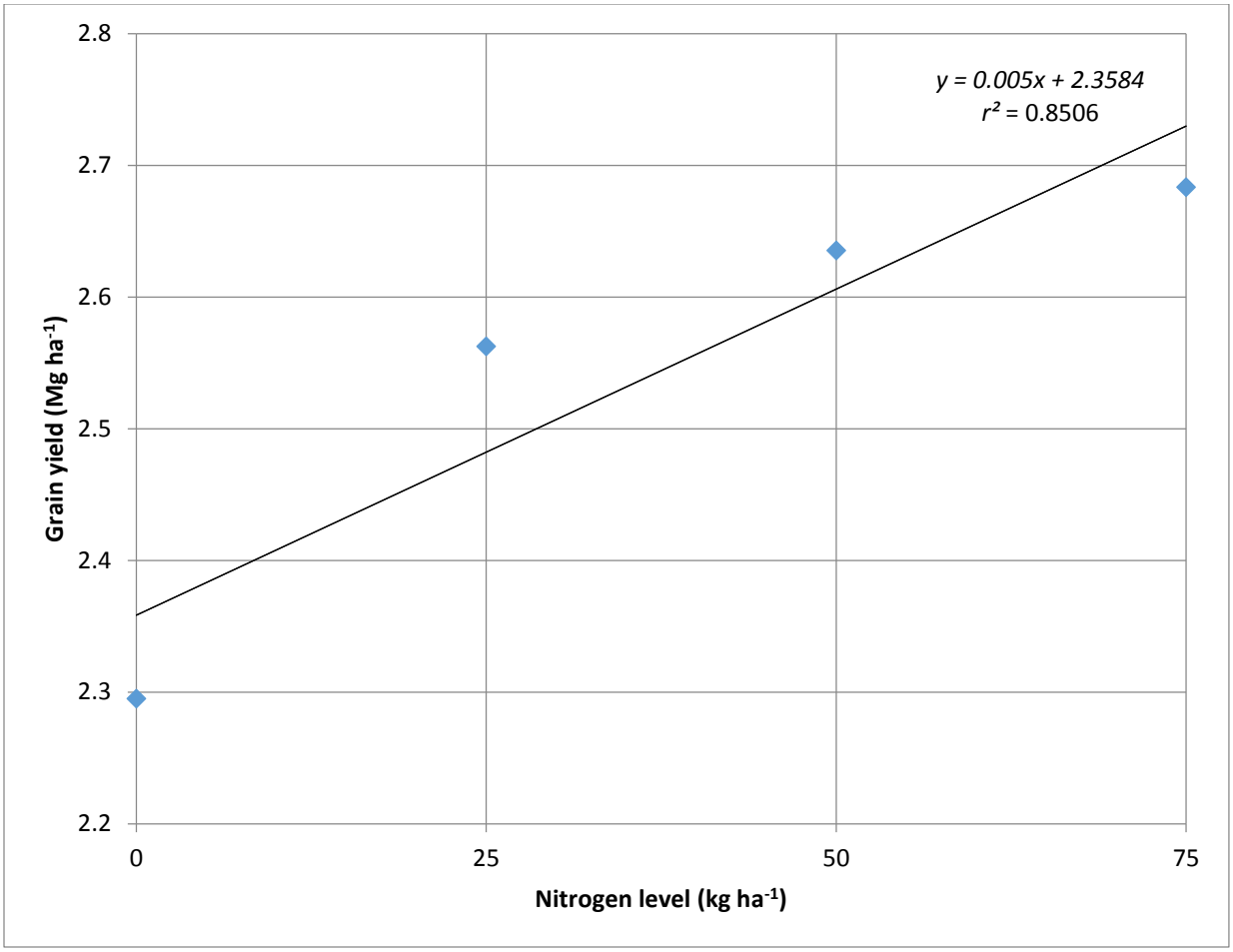

Figure 3. Effect of nitrogen fertilizer treatment on grain yield (Mg ha^{-1}) across height classes, protein classes, and four dryland environments.

Grain protein concentration

Averaged across height classes and environments, mean grain protein concentration (GPC) of the conventional protein class ranged from 9 to 16 g kg^{-1} higher than that of the low-protein class (Table 7). According to the American Malting Barley Association (AMBA), 135 g kg^{-1} is the maximum acceptable GPC for malting barley. Mean grain protein levels were acceptable for the low-protein class at all environments, except 2006 Richardton. The grain protein level for conventional protein genotypes was unacceptable at all locations except 2005 Minot, where the mean grain protein content was at the maximum acceptable level of 135 g kg^{-1}.

Table 6. Mean grain protein content of conventional and low-protein classes combined across height classes, four nitrogen levels, and four dryland environments.

	Protein class	
Environment	Conventional	Low
	----------g kg^{-1}----------	
2005 Minot	135 d†	121 a
2005 Williston	140 e	124 b
2006 Richardton	159 g	145 f
2006 Williston	141 e	132 c

†Means in the table followed by the same letter are not significantly different ($P \leq 0.05$) as determined using *t*-tests between each pair of treatments.

Grain protein content was also significantly higher ($P \leq 0.05$) for the semi-dwarf class when compared to the conventional height class. The grain protein of the semi-dwarf class was 139 g kg^{-1}, while the grain protein of the conventional height class was 135 g kg^{-1}. This is probably due to slight inherent differences of individual genotypes that make up each height group, rather than a pleiotropic effect of the semi-dwarf trait on GPC. The gene responsible for the semidwarf trait in the genotypes evaluated is the *sdw1* that is in the long arm of chromosome 3H (Haahr and von Wettstein 1976; Barua et al. 1993; Laurie et al. 1993; Mickelson and Rasmusson 1994; Hellewell et al. 2000; Jia et al. 2009; Kuczyńska et al. 2013). The QTL responsible for the low-protein character in the present study's genotype is located in the centromeric region of chromosome 6H (See et al., 2002).

As nitrogen fertilizer rate increased, GPC also increased across protein and height classes (Figure 4). For each kg ha^{-1} of N added, GPC increased by 0.29 g kg^{-1} (Figure 5). Weston et al. (1993) found that grain protein increased by 0.11 g kg^{-1} for every kg ha^{-1} of nitrogen that was added in eastern North Dakota environments. The effects on grain protein content due to addition of more nitrogen may be more pronounced in western North Dakota environments where average precipitation is typically less than in eastern North Dakota. Experiments conducted primarily in the Eastern North Dakota environment by Weston et al. (1993) received

24 % more precipitation during the growing season than this experiment conducted in the western North Dakota environment. Current NDSU soil fertilizer recommendations for malting barley grown in eastern North Dakota and far northern North Dakota recommend 77.16 kg ha^{-1} of nitrogen for every tonne of yield goal (Franzen and Goos, 2007). For warmer and drier environments in Western North Dakota, the recommendations are for 61.55 kg ha^{-1} of nitrogen for every tonne of yield goal. Under dry growing conditions barley does not utilize all of the available nitrogen in the soil, sometimes resulting in barley with excessively high GPC that may be rejected by the malting industry.

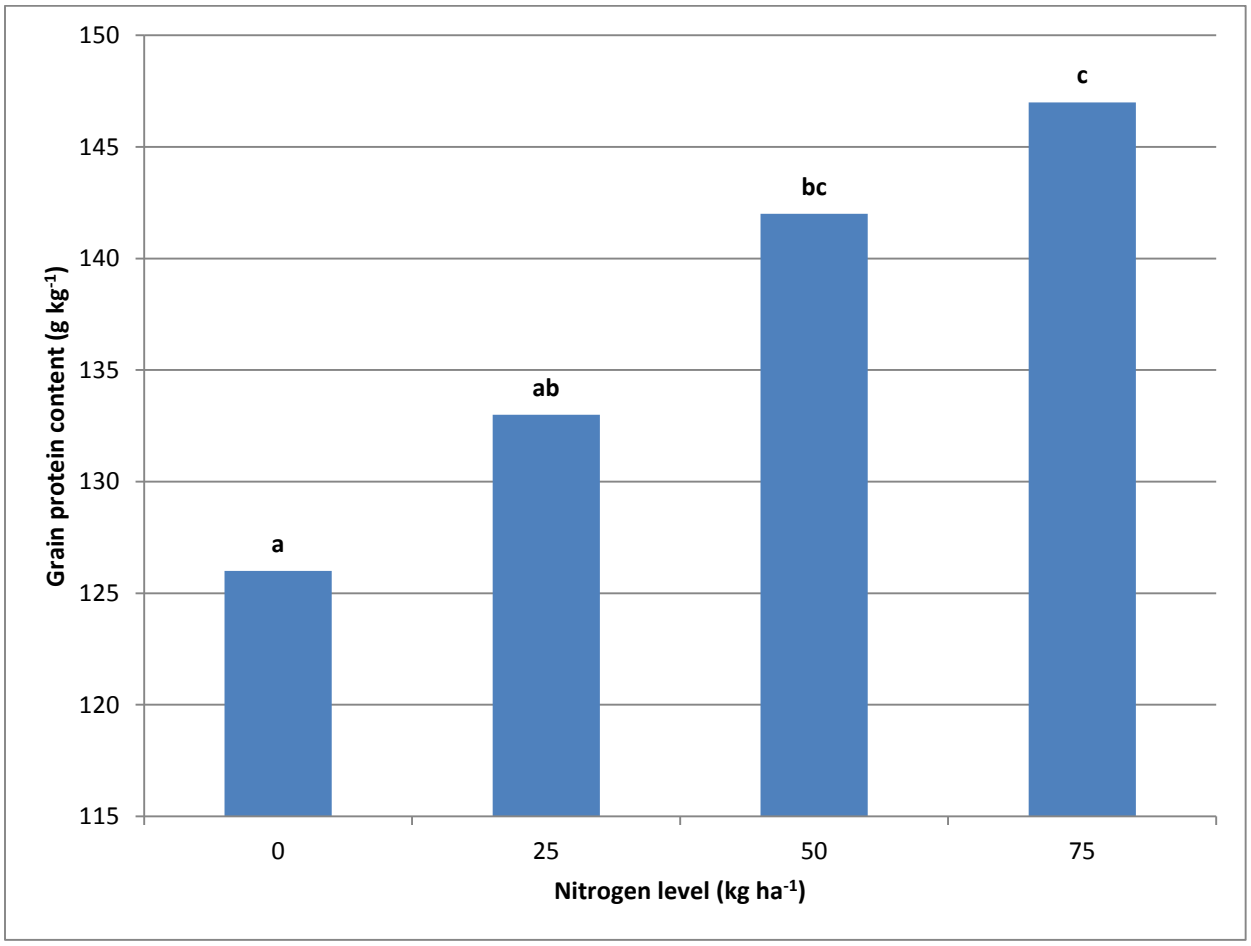

Figure 4. Grain protein content (g kg^{-1}) combined across protein classes, height classes, and four dryland environments arranged by nitrogen level. Bars topped by the same letter are not significantly different ($P \leq 0.01$).

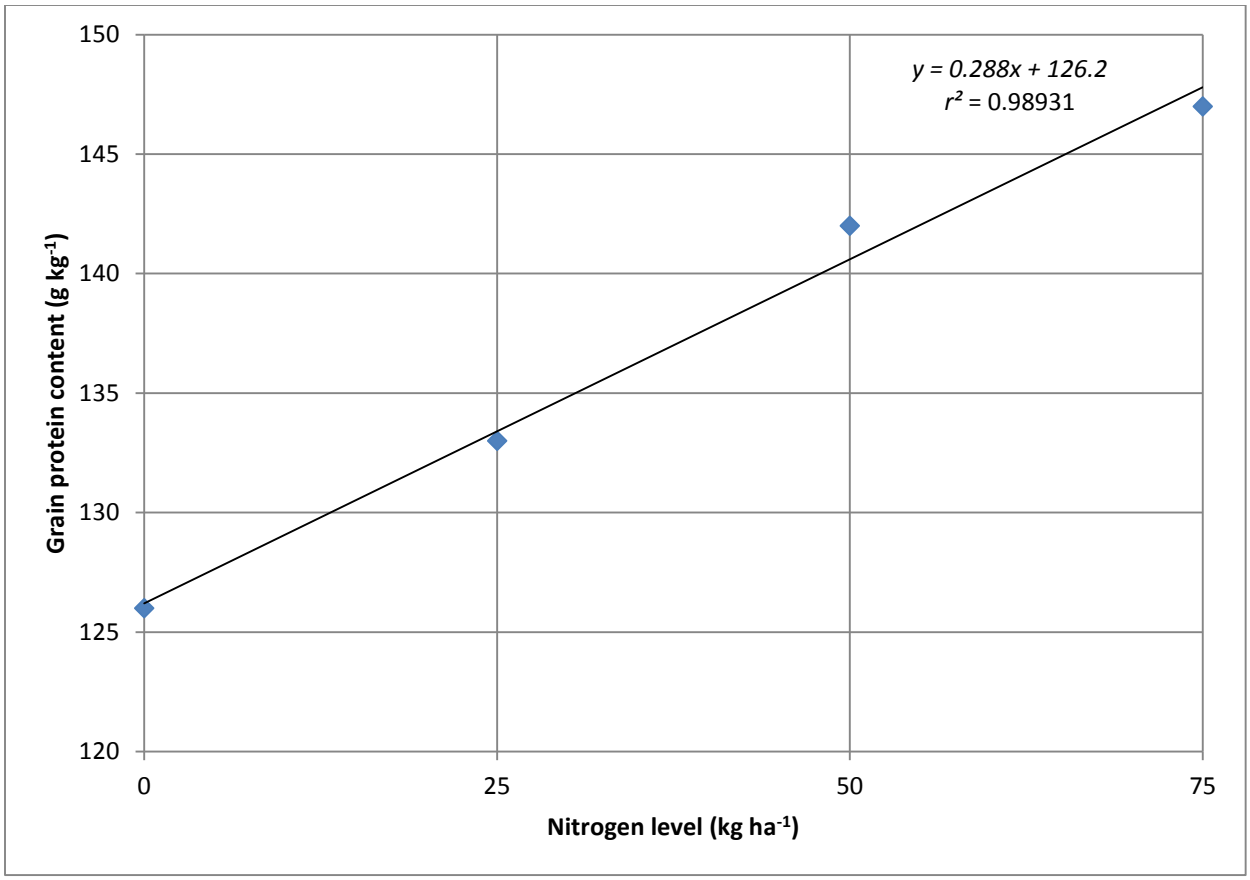

Figure 5. Effect of nitrogen fertilizer treatment on grain protein content (g kg^{-1}) across height classes, protein classes, and four dryland environments.

Grain color

Protein class was found to have a significant ($P \leq 0.05$) effect on grain color, regardless of height class. Lower color scores indicate darker kernel color, which is an undesirable trait in malting barley cultivars. Buyers of malting barley are trained to look for brightly colored barley, because dark kernel color typically is associated with kernel disease and mold. Anderson and Banttari (1976) found that grain yield and kernel weight reductions were associated with poor kernel color in barley genotypes inoculated with *Bipolaris sorokiniana* (Sacc.) Shoemaker. High protein, low malt extract, dark wort color, and beer taste and aroma problems have been associated with kernel discoloration (Gebhardt et al., 1992). Averaged across height classes, the color scores for the low protein group and conventional protein group were 55.0 and 55.6 °L,

respectively. Experimental lines used in this experiment were developed by the North Dakota State University (NDSU) barley-breeding program. The low protein characteristic of these lines can be traced back to the cultivar Karl. Progenies originating from Karl are known to have darker grain color, which has proven to be a problem in cultivar development in the NDSU breeding program (Goblirsch et al., 1996).

As the level of nitrogen fertilizer increased, grain color became darker. The mean grain color for genotypes receiving the 25 kg ha^{-1} treatment was significantly ($P \leq 0.05$) brighter than the mean color of genotypes receiving the 50 and 75 kg ha^{-1} treatment (Figure 6). To the best of my knowledge, this is the first finding that increasing nitrogen fertilizer rate was associated with darker kernels.

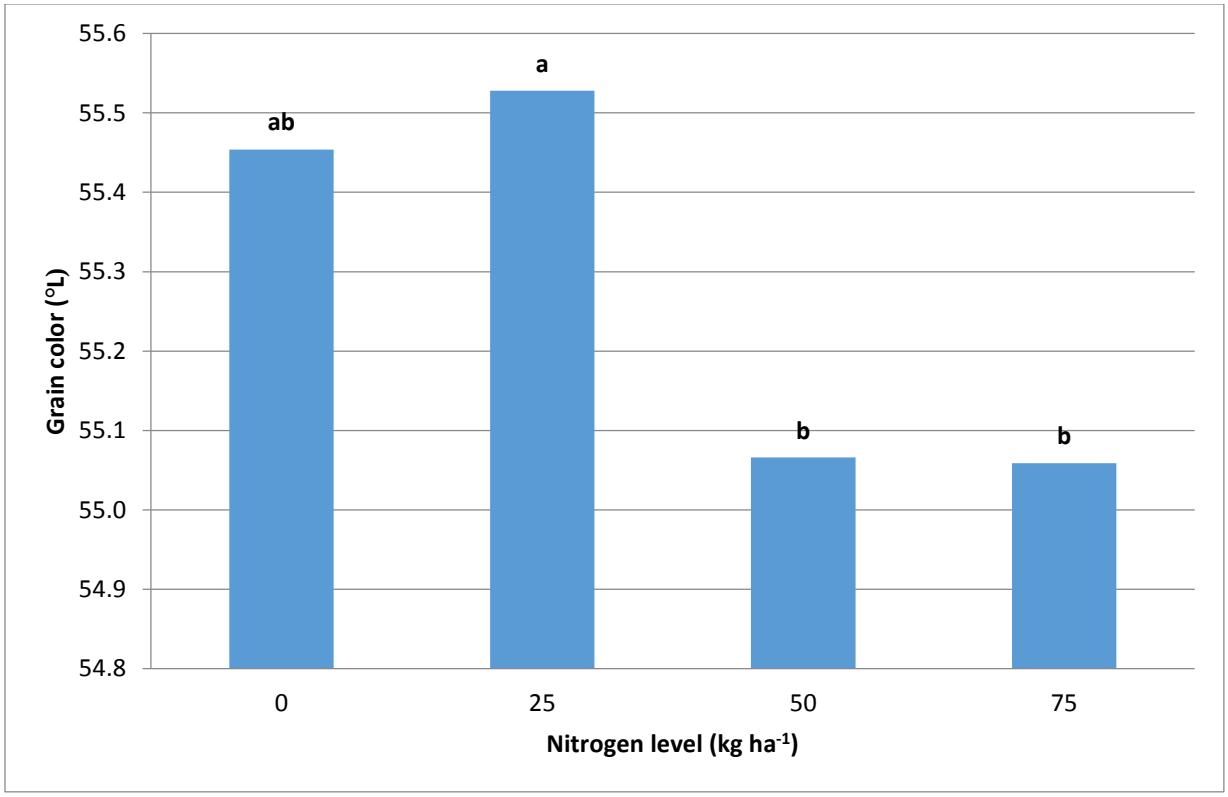

Figure 6. Grain color (°L) combined across height classes, protein classes, and four dryland environments arranged by nitrogen level. Bars topped by the same letter are not significantly different ($P \leq 0.05$).

Straw nitrogen content

Protein class was a significant ($P \leq 0.05$) factor in regards to straw nitrogen content. Straw nitrogen content was 10.95 and 12.08 g kg^{-1} for the conventional and low protein classes, respectively, indicating that the low protein genotypes stored higher amounts of nitrogen in vegetative parts than the conventional protein genotypes. Erickson et al. (1982) found similar results when measuring the straw nitrogen levels of Karl and other commonly grown Midwestern malting barley cultivars. Karl had straw nitrogen levels that were three percentage points higher than the next highest cultivar. Because Karl is known to have low GPC, the author concluded that Karl and other low protein cultivars are not as efficient in nitrogen translocation as conventional protein cultivars.

Nitrogen was also a highly significant ($P \leq 0.01$) factor in straw nitrogen concentration. Straw nitrogen concentration of the 75 kg ha^{-1} nitrogen treatment was significantly ($P \leq 0.01$) higher than those of the 0 and 25 kg ha^{-1} nitrogen fertilizer regimens (Figure 7). As nitrogen fertilizer level increased, straw nitrogen concentration increased. Straw nitrogen increased 0.059 g kg^{-1} for every kg ha^{-1} nitrogen applied (Figure 8). Findings in an experiment conducted by Grant et al. (1991) found that straw nitrogen concentrations increased as nitrogen fertilizer level increased, regardless of moisture conditions.

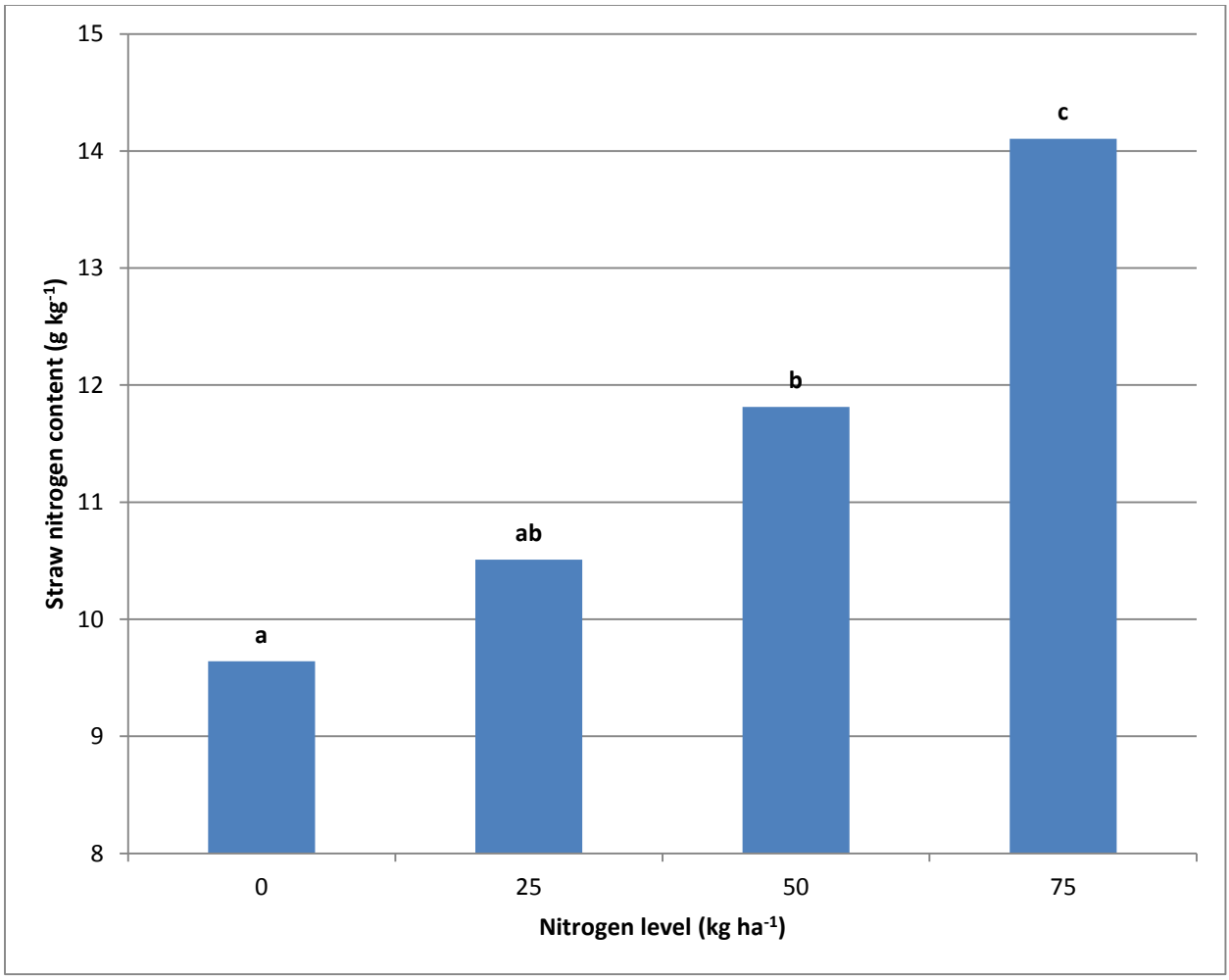

Figure 7. Straw nitrogen content (g kg^{-1}) combined across protein classes, height classes, and four dryland environments arranged by nitrogen level. Bars topped by the same letter are not significantly different ($P \leq 0.05$).

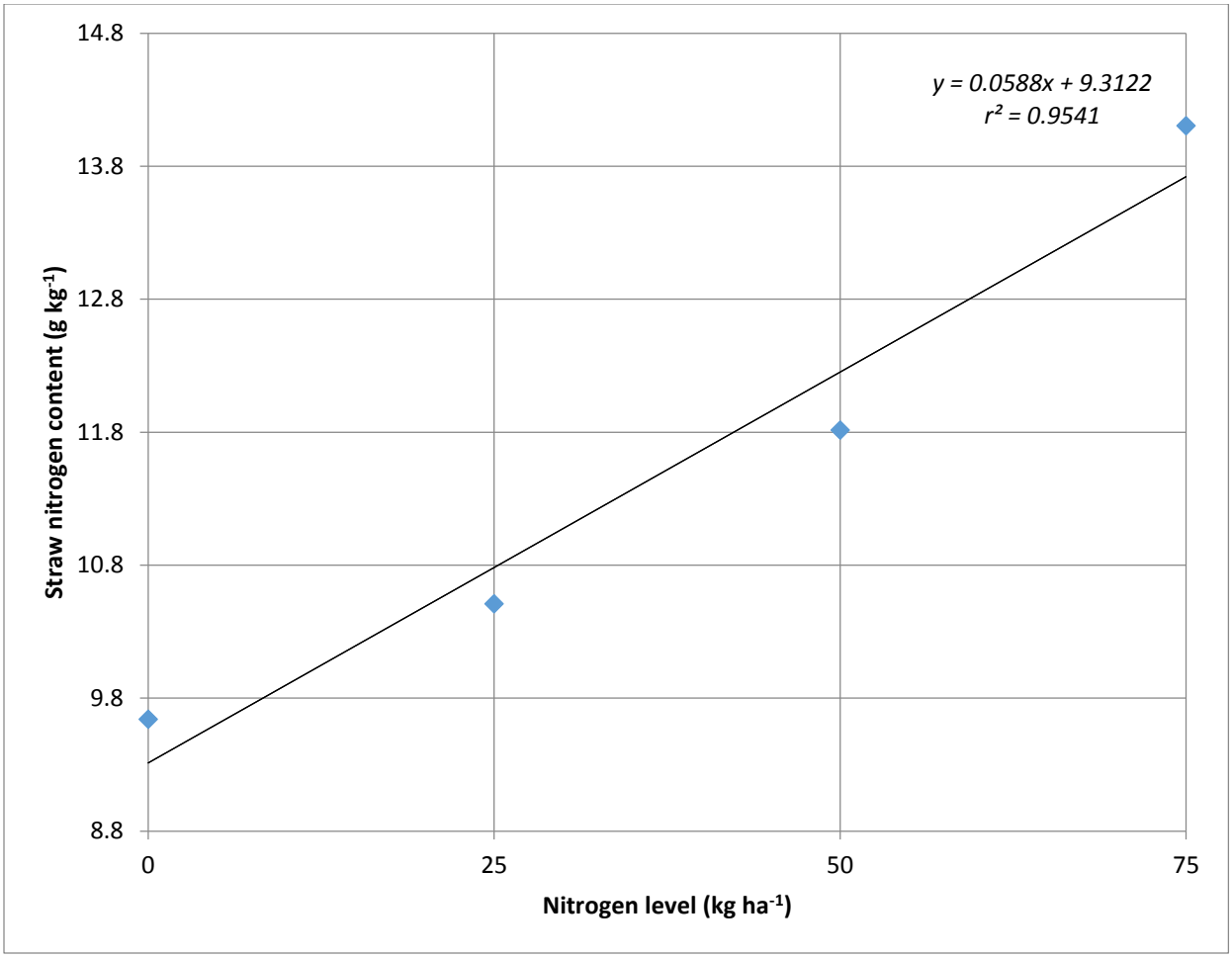

Figure 8. Effect of nitrogen fertilizer treatment on straw nitrogen content (g kg^{-1}) across height classes, protein classes, and four dryland environments.

Total nitrogen uptake

Low protein genotypes took up significantly ($P \leq 0.01$) less nitrogen than conventional protein genotypes across nitrogen levels. Total nitrogen uptake was 140.7 kg ha^{-1} for low-protein genotypes and 150.3 kg ha^{-1} for conventional protein genotypes. These results suggest that low-protein genotypes may be less efficient than their conventional protein counterparts in nitrogen uptake. The mechanism for this inefficiency in low-protein genotypes derived from 'Karl' has not been studied.

Nitrogen rate also significantly ($P \leq 0.01$) affected total nitrogen uptake. As nitrogen fertilizer rates increased, total nitrogen uptake also increased (Figure 9). Similar results were obtained in experiments conducted by Delogu et al. (1998) with winter wheat and winter barley. In this study, nitrogen uptake increased with increasing rates of nitrogen fertilizer up to 140 kg ha^{-1} at the heading (Feekes 10.1), soft dough (Feekes 11.2), and maturity (Feekes 11.4) growth stages. There were no differences in total nitrogen uptake at tillering (Feekes 2), regardless of nitrogen level. Total nitrogen uptake at tillering was less than 40 kg ha^{-1}, but increased to 210 kg ha^{-1} at maturity.

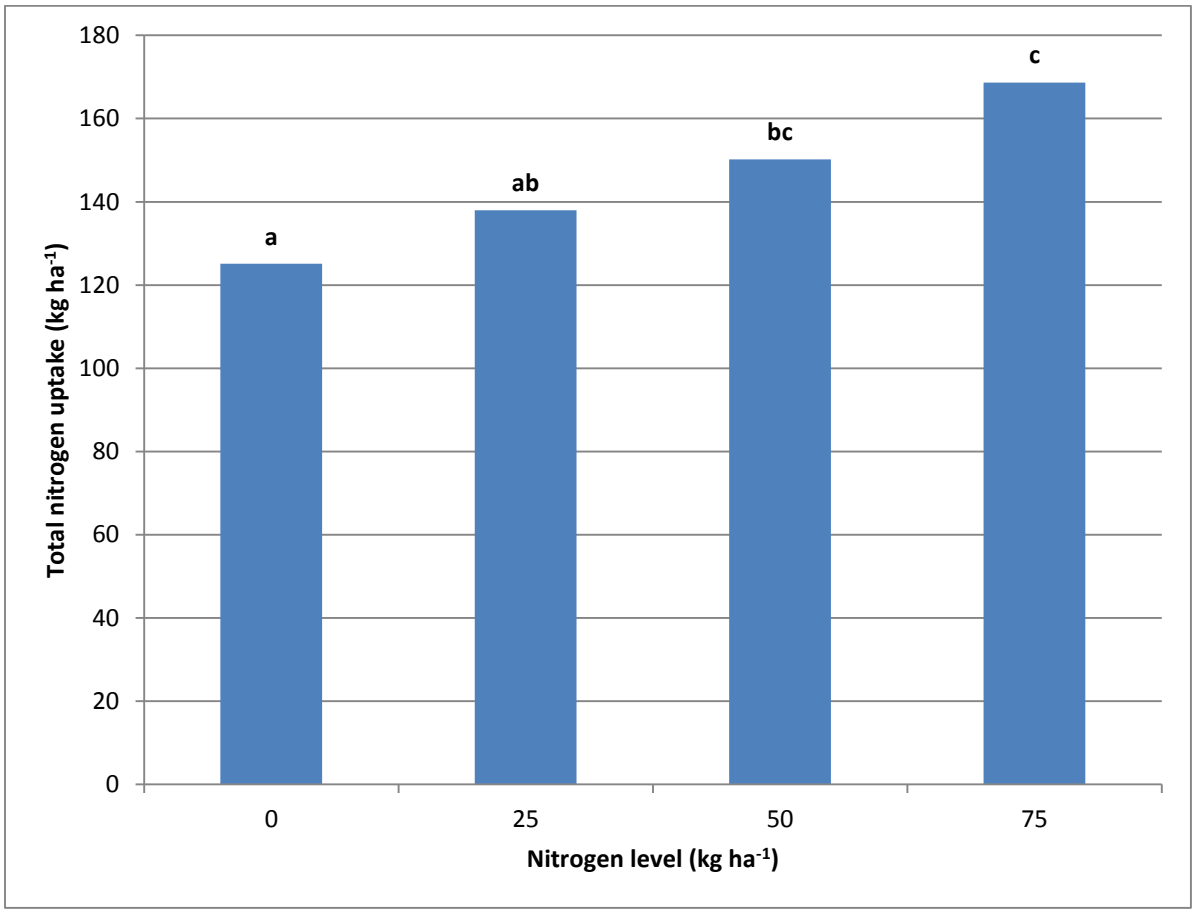

Figure 9. Total nitrogen uptake (kg ha^{-1}) combined across protein classes, height classes, and four dryland environments arranged by nitrogen level. Bars topped by the same letter are not significantly different ($P \leq 0.05$).

Nitrogen harvest index

Conventional protein genotypes had significantly ($P \leq 0.05$) higher nitrogen harvest index values (NHI) than low-protein genotypes across nitrogen levels. Nitrogen harvest index was 0.62 for the conventional protein class and 0.56 for the low-protein class. Nitrogen harvest index is calculated by dividing grain nitrogen yield by total nitrogen uptake and has been suggested as a selection criterion for GPC (Loffler and Busch, 1982). High NHI indicates increased partitioning of the total nitrogen uptake to grain (Bulman and Smith, 1994).

The amount of nitrogen applied also was a significant ($P \leq 0.05$) factor in determining NHI. As nitrogen fertilizer rates increased, NHI decreased (Figure 10). The NHI was significantly less at the 75 kg ha^{-1} rate of nitrogen than any other nitrogen fertilizer rate. Hoseinlou et al. (2013) also observed that increasing rates of N reduced NHI under dry conditions. In this study, NHI was affected mainly by moisture and nitrogen rate. The lowest NHI was obtained under irrigated conditions. Grain yield also increased as nitrogen rate increased. A reduced NHI would indicate less of the total nitrogen uptake was partitioned to grain.

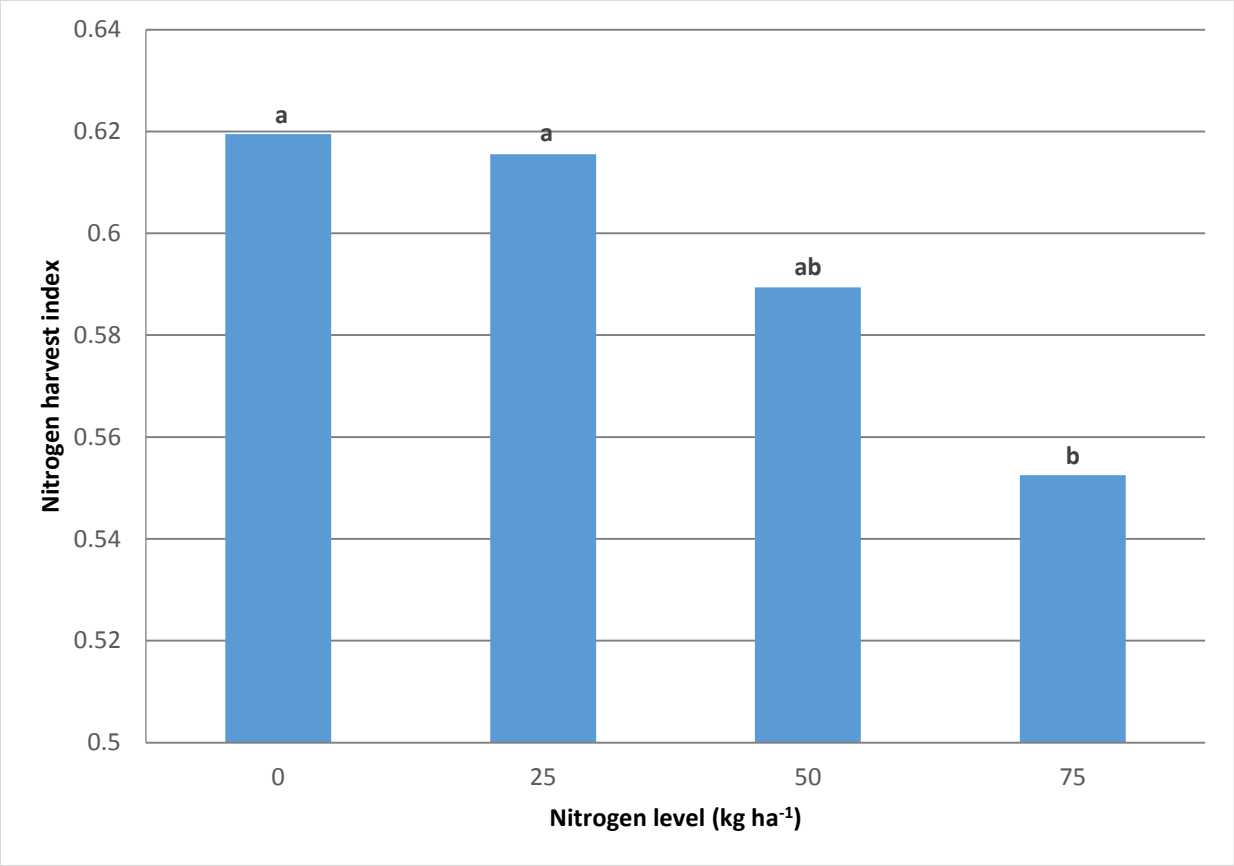

Figure 10. Nitrogen harvest index (NHI) combined across height classes, protein classes, and four dryland environments arranged by nitrogen level. Bars topped by the same letter are not significantly different ($P \leq 0.05$).

Irrigated Experiment

Plant height

Averaged across protein classes, conventional height genotypes were significantly ($P \leq 0.05$) taller than semidwarf genotypes. Plant height for conventional and semidwarf height classes were 70.7 and 61.9 cm, respectively. Moreover, the addition of nitrogen fertilizer significantly ($P \leq 0.05$) increased plant height. Plants receiving the 0 kg ha^{-1} nitrogen treatment were significantly shorter than those receiving all of the other nitrogen treatments (Figure 11). Plant height is known to increase with increasing rates of nitrogen fertilizer. In an experiment

conducted by Weston (1992), increases in nitrogen fertilizer rate significantly increased plant height.

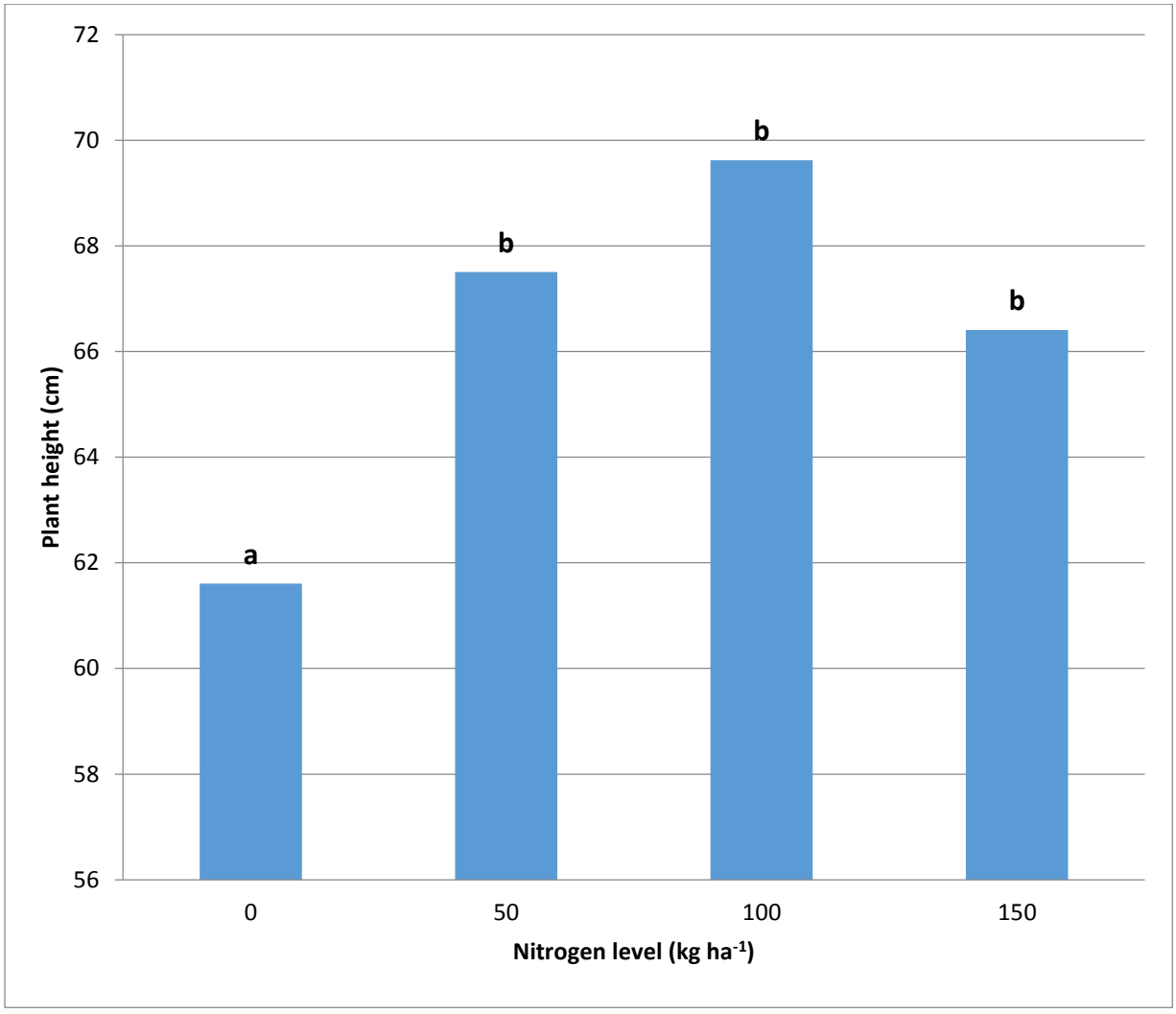

Figure 11. Plant height (cm) combined across protein classes, height classes, and four dryland environments arranged by nitrogen level. Columns topped by the same letter are not significantly different ($P \leq 0.05$).

Days to heading

The environment x height class interaction was highly significant ($P \leq 0.01$) for heading date. The days to heading for conventional and semidwarf lines did not differ significantly in the 2007 Nesson Valley environment, but the conventional lines headed significantly earlier than semidwarf lines in the 2006 Nesson Valley environment (Table 7). The environment x protein

class interaction was also highly significant ($P \leq 0.01$) for heading date. Conventional protein lines headed significantly earlier than low protein lines in the 2006 Nesson Valley environment, but headed later than low protein lines in the 2007 Nesson Valley environment (Table 8).

Table 7. Mean days to heading combined across protein classes and nitrogen rates, arranged by environment and height class.

	Height class	
Environment	Conventional	Semidwarf
	----------days after May 31----------	
2006 Nesson Valley	22.3 b†	24.0 c
2007 Nesson Valley	20.0 a	19.6 a

†Means in the table followed by the same letter are not significantly different ($P \leq 0.05$) as determined using t-tests between each pair of treatments.

Table 8. Mean days to heading combined across height classes and nitrogen rates, arranged by environment and protein class.

	Protein class	
Environment	Conventional	Low
	----------days after May 31----------	
2006 Nesson Valley	22.9 c†	23.4 d
2007 Nesson Valley	20.2 b	19.4 a

†Means in the table followed by the same letter are not significantly different ($P \leq 0.05$) as determined using t-tests between each pair of treatments

Grain yield

No significant differences in grain yield were detected for the height class, protein class, and height x protein class sources of variation. Semidwarf genotypes performed as well as conventional genotypes in regards to grain yield under irrigation. Likewise, low-protein genotypes yielded similarly to conventional-protein genotypes. These results indicate that the semidwarf, low-protein genotypes are not at a yield disadvantage to conventional height, conventional protein genotypes in Western North Dakota irrigated conditions.

Grain yield was not significantly influenced by nitrogen fertilizer application in this experiment. However, grain yield was numerically higher when nitrogen fertilizer was applied versus the 0 kg ha^{-1} treatment (Figure 12). The grain yield response of barley cultivars to

nitrogen fertilizer has been extensively researched and is known to increase with increasing rates of nitrogen fertilizer (Lauer and Partridge, 1990; Weston et al., 1993; Emebiri and Moody, 2004; O'Donovan, 2011). Additional research is needed in North Dakota to determine the response of semidwarf and low protein genotypes under irrigated production.

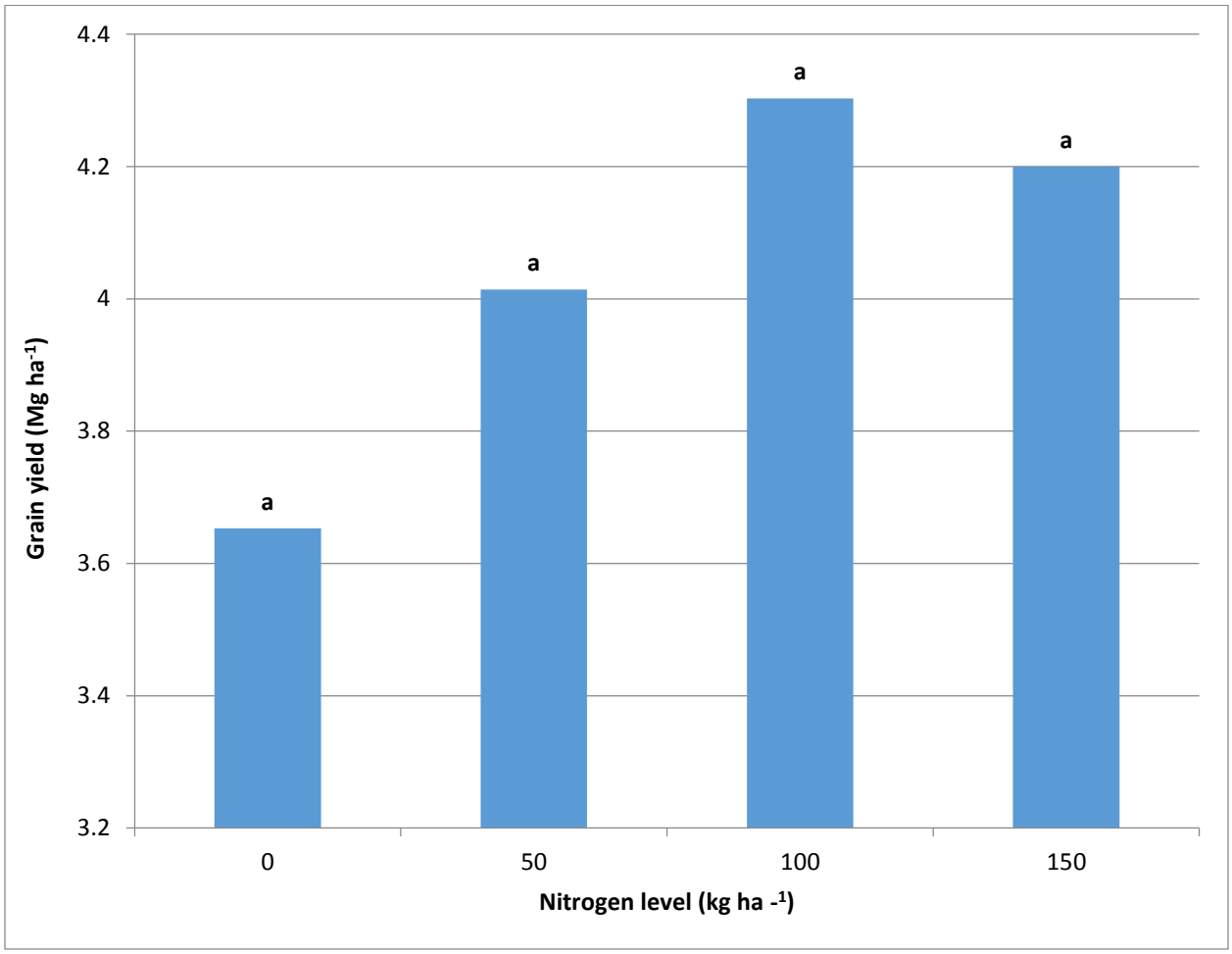

Figure 12. Grain yield (Mg ha^{-1}) combined across height and protein classes, and two irrigated environments arranged by nitrogen level. Columns topped by the same letter are not significantly different ($P \leq 0.05$).

Grain protein concentration

No significant differences in GPC were detected for the height class or protein class main effects, or the height x protein class interaction. The fact that the GPC of semidwarf and

conventional height genotypes did not differ indicates that semidwarf lines are not at a disadvantage to conventional lines for GPC under an irrigated production regime. The GPC of conventional and semidwarf genotypes were both within the acceptable range of grain buyers, with protein levels of 125 g kg^{-1} and 133 g kg^{-1}, respectively.

Combined across height classes, the GPC of the low-protein genotypes was numerically, but not significantly lower than that of the conventional-protein genotypes. However, the GPC of the low-protein class (120 g kg^{-1}) was acceptable protein for malting barley, while the GPC of 137 g kg^{-1} was not. Production of low protein genotypes could make the difference between acceptance and rejection by a buyer of malting barley in a particular growing season, which could impact the sale price of the grain. Barley sold for malting commands a higher price than non-malting barley in North Dakota.

The application of nitrogen fertilizer was not a statistically significant factor in increasing GPC in the irrigated experiment. Grain protein concentration values tended to increase as nitrogen fertilizer rates increase (Figure 13), but GPC levels were below the 135 g kg^{-1} threshold set by grain buyers at all levels of nitrogen fertilizer application. This suggests that even higher rates of nitrogen fertilizer could have been used without having the GPC levels exceeding 135 g kg^{-1}. Birch and Long (1990) found that GPC of malting-type cultivars grown under irrigated conditions had acceptable levels of protein ($\leq$ 11.5%) at nitrogen rates up to 200 kg ha^{-1}.

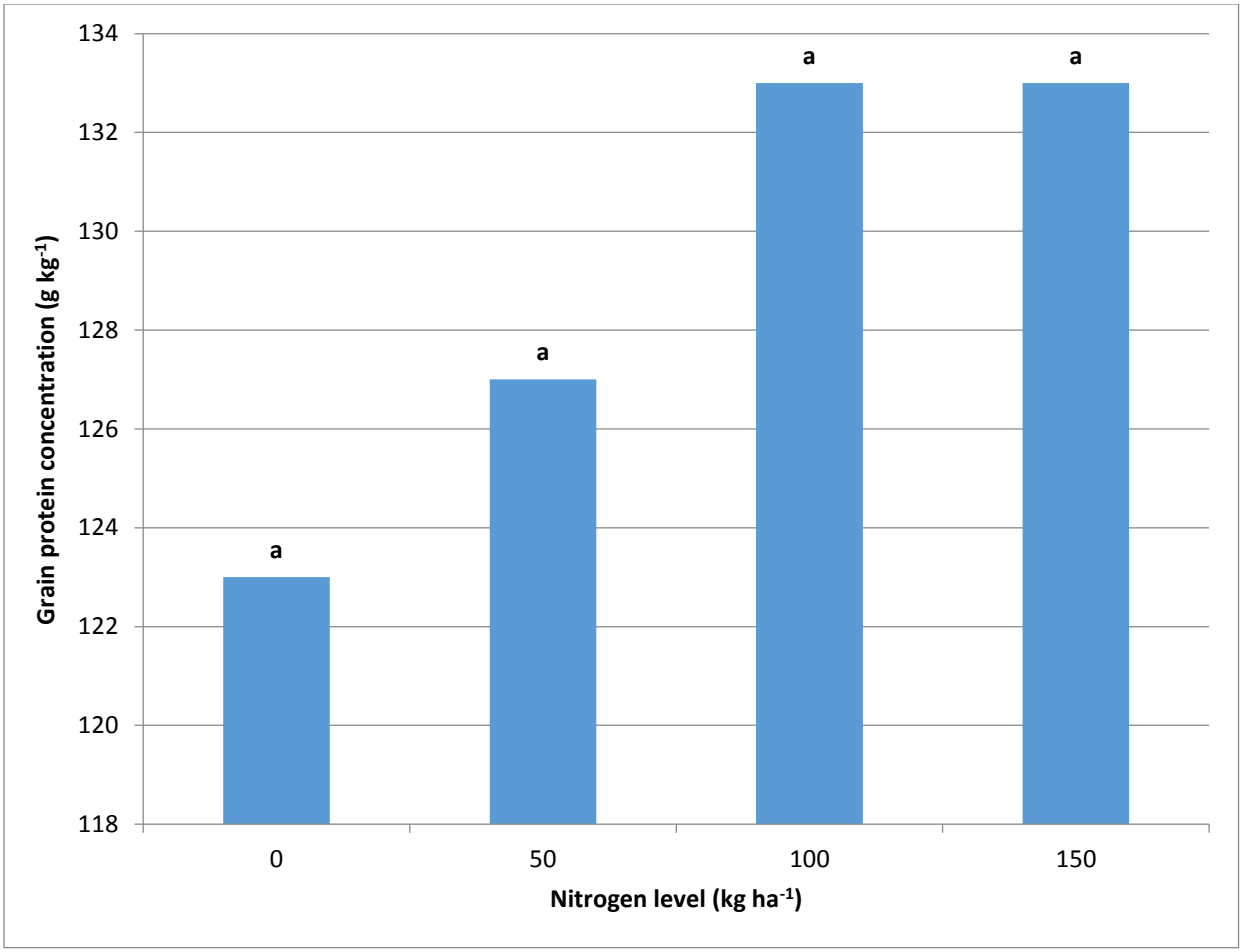

Figure 13. Grain protein concentration (g kg-1) combined across protein and height classes, and two irrigated environments, arranged by nitrogen level. Columns topped by the same letter are not significantly different ($P \leq 0.05$).

Grain color

The environment x height class interaction was highly significant ($P \leq 0.01$) for grain color. Semidwarf genotypes had significantly brighter grain color than conventional height genotypes in both 2006 and 2007 Nesson Valley environments. The magnitude of this difference depended on the environmental conditions (Table 9).

Table 9. Grain color combined across protein class and nitrogen level, arranged by environment and height class.

Environment	Height class		
	Conventional	Semidwarf	Difference
	----------°L----------		
2006 Nesson Valley	56.7 b†	57.5 a	0.8
2007 Nesson Valley	51.7 d	51.8 c	0.1

†Means in the table followed by the same letter are not significantly different (P≤0.05) as determined using t-tests between each pair of treatments.

The height x protein class interaction was also significant (*P*≤0.05) for grain color. The conventional height, low-protein group had a significantly (*P*≤0.05) darker grain color than the other three height x protein combinations (Table 10). Low-protein lines that are progeny of the low protein parent 'Karl' are known to have poor grain color (Goblirsch et al., 1996). The semidwarf, low-protein group in this experiment had the brightest grain color. However, one needs to be careful drawing conclusions from this observation because there were only two genotypes in this class. Goblirsch et al. (1996) stated that the breeding strategy used by the NDSU barley-breeding program at the time was successful in identifying low-protein, Karl-derived genotypes with acceptable kernel color. The release of successful low-protein cultivars from the NDSU barley-breeding program such as Rawson, Pinnacle, and ND Genesis are evidence of progress made in coupling acceptable grain color with the low-protein trait.

Table 10. Grain color combined across nitrogen levels and two irrigated environments, arranged by protein and height class.

Protein class	Height class	
	Conventional	Semidwarf
	----------°L----------	
Conventional	55.0 a†	54.2 ab
Low	53.4 b	55.1 a

†Means in the table followed by the same letter are not significantly different (P≤0.05) as determined using t-tests between each pair of treatments.

The protein class x nitrogen interaction also was significant ($P \leq 0.01$) for grain color. The conventional-protein genotypes had brighter grain color than low-protein genotypes at all nitrogen levels except the 100 kg ha^{-1} rate (Figure 14). Additionally, the addition of nitrogen fertilizer had a negative impact on grain color, especially in the conventional protein group. The conventional protein genotypes had the brighter grain color when no additional nitrogen fertilizer was added. The low-protein genotypes had significantly brighter grain color at the 100 kg ha^{-1} nitrogen level than at 0 and 150 kg ha^{-1}.

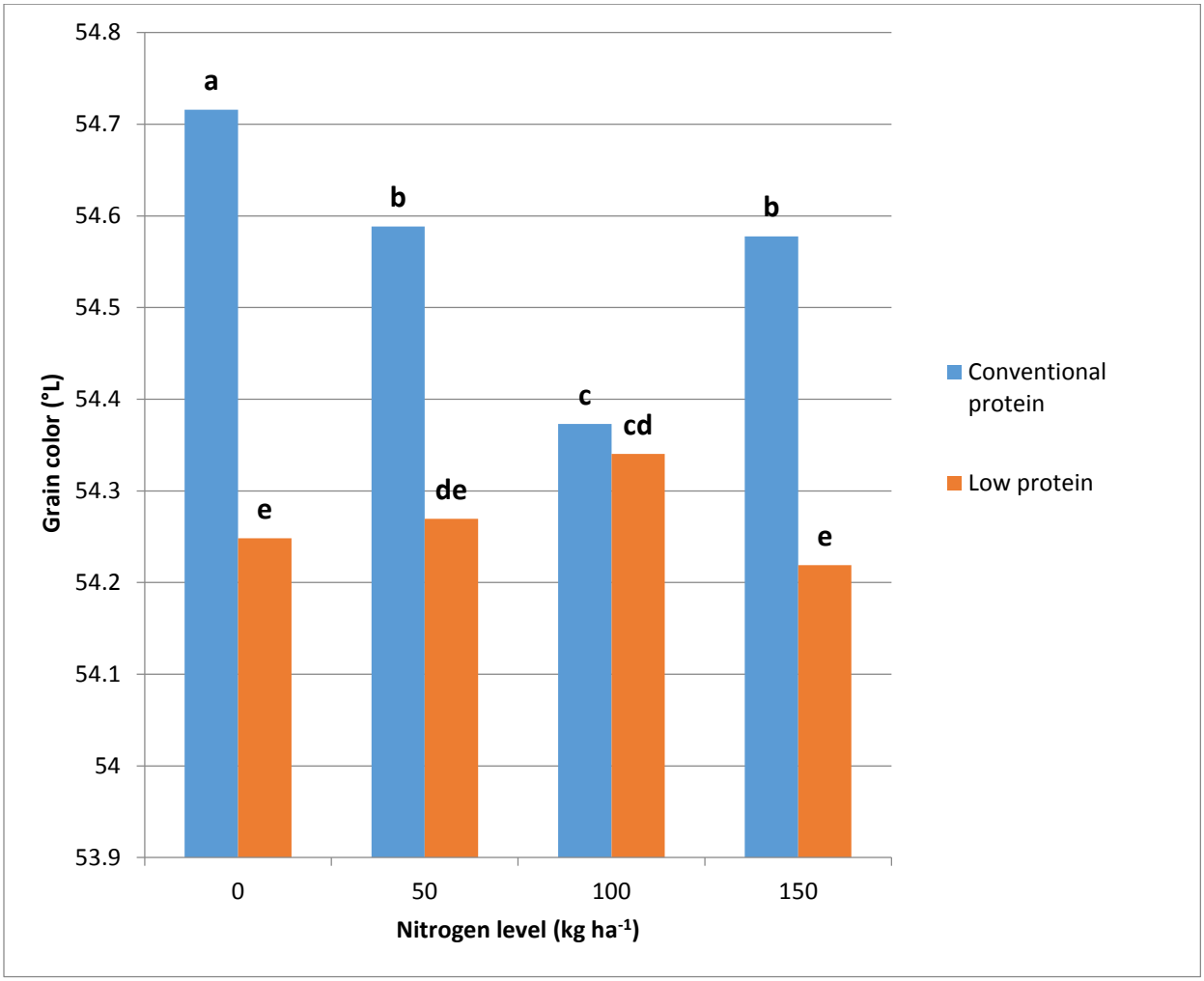

Figure 14. Grain color (°L) combined across height classes and two irrigated environments, arranged by protein class and nitrogen level. Columns topped by the same letter are not significantly different ($P \leq 0.05$).

Straw nitrogen content

The protein class x nitrogen interaction was significant ($P \leq 0.05$) for straw nitrogen content. The conventional-protein lines had significantly lower straw nitrogen content than the low-protein lines at all levels of nitrogen fertilizer (Figure 15). The magnitude of this difference varied depending on nitrogen level. Straw nitrogen content increased as nitrogen fertilizer levels increased, regardless of protein class. The conventional protein class had significant increases in straw nitrogen content with every incremental increase of 50 kg ha^{-1} of nitrogen fertilizer. For the low-protein class, the 0 and 50 kg ha^{-1} fertilizer rates had significantly lower straw nitrogen content than those for the 100 and 150 kg ha^{-1} rates. Previous research found that straw nitrogen content of Karl-derived low-protein lines had straw nitrogen content at least three percentage points higher than those of conventional GPC lines (Erickson et al., 1982). In 1991, Grant et al. found that straw nitrogen concentrations are positively correlated to increasing nitrogen fertilizer rates, regardless of moisture conditions.

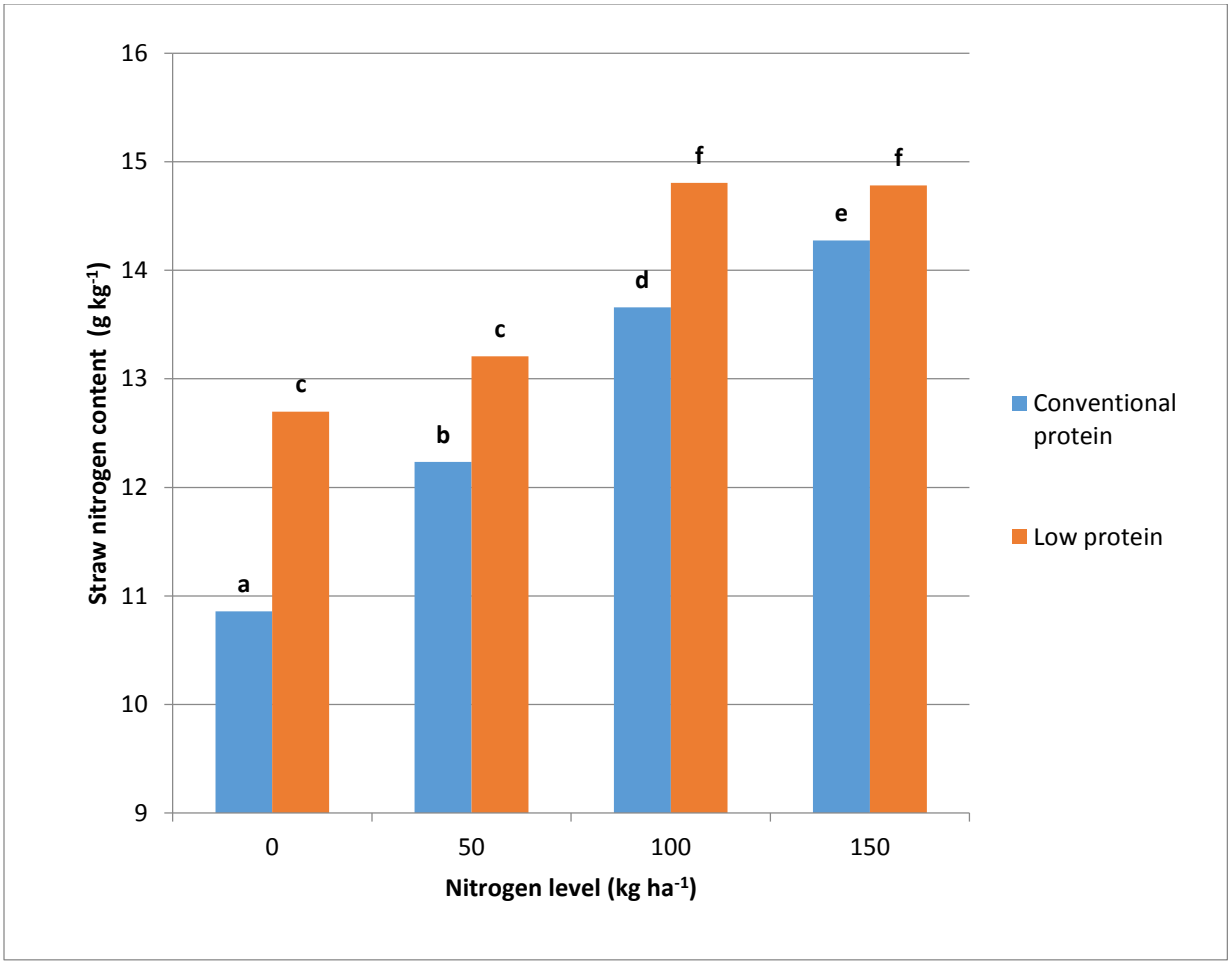

Figure 15. Straw nitrogen content (g kg-1) combined across height classes, and two irrigated environments, arranged by protein class and nitrogen level. Columns topped by the same letter are not significantly different ($P \leq 0.05$).

SUMMARY AND CONCLUSIONS

Barley production has shifted from eastern North Dakota to western North Dakota, primarily due to increased occurrences of Fusarium head blight. Producing malting barley in western North Dakota brings with it a set of new and unique challenges. Warmer temperatures and lower precipitation in western North Dakota increases the chance of barley being rejected for high GPC and thin kernels. Rejected grain is usually sold into the feed barley market at a steep discount, which equates to lower per hectare returns or even a negative return. According to the USDA-NASS (2014), feed barley was sold at a $57.41 per tonne ($1.25 per bushel) average discount versus malting barley in the marketing years 2008-2013. Cultivars are being developed for production in western North Dakota as part of the Western Malting Barley Initiative. These cultivars will have genes, derived from 'Karl', which lowers grain protein by up to two percentage points as compared to conventional protein cultivars. In addition, semidwarf genes will be incorporated into cultivars intended for irrigated production to reduce the chances of lodging under irrigated growing conditions.

This research answers major questions about low-protein and semidwarf genotypes as compared to their conventional protein and conventional height counterparts under dryland and irrigated production conditions in western North Dakota. In addition, low-protein genotypes were further compared to conventional protein genotypes to determine if any differences in nitrogen translocation exist. Low-protein genotypes researched in this project, and new low-protein cultivars should help producers increase the chances of selling barley that is accepted for malting. Highlights of this research are listed below:

1. Low-protein genotypes have the obvious benefit of having inherently low GPC. In the dryland experiments conducted for this thesis, conventional protein genotypes had

unacceptable GPC at all locations except for one, which had the maximum acceptable GPC of 135 g kg^{-1}. By contrast, low-protein genotypes had acceptable GPC at three of four locations. Under the irrigated production regime, there were no significant differences detected between protein classes for grain protein. However, when averaged across height classes, nitrogen levels, and environments, the low-protein genotypes had an acceptable GPC (120 g kg^{-1}), while the conventional protein genotypes had an unacceptable GPC (137 g kg^{-1}). By utilizing low-protein genotypes in a dryland or irrigated production system, barley producers can increase their chances of making malting grade and ultimately making a profit.

2. Low-protein genotypes did not differ significantly from conventional protein genotypes in regards to grain yield in dryland and irrigated experiments. In addition, the grain yield of semidwarf genotypes did not differ significantly from conventional height genotypes, and all height and protein class combinations yielded similarly to each other. These results indicate that low-protein and semidwarf genotypes are not at a disadvantage for grain yield when compared to their conventional counterparts.
3. Low-protein genotypes had darker kernel colors than their conventional protein counterparts. This is considered an undesirable trait in malting barley. Buyers of malting barley are trained to look for brightly colored barley, because dark kernel color typically is associated with kernel disease and mold. It is unlikely, however, that barley would be rejected for malting due to dark kernel color alone.
4. Semidwarf genotypes showed no yield disadvantages when compared to their conventional height counterparts in dryland or irrigated conditions. Semidwarf genotypes did have higher GPC than conventional height genotypes in the dryland experiment; however, this is

probably due to slight inherent differences found in the individual genotypes that make up each group rather than a pleiotropic effect of semidwarf height genes on GPC. Semidwarf and conventional height genotypes performed similar to each other in all other measured traits. Not surprisingly, conventional height genotypes were taller than semidwarf genotypes under dryland and irrigated conditions.

5. Low-protein genotypes differ from conventional protein genotypes in regards to nitrogen translocation at maturity. Conventional protein genotypes had higher GPC than low-protein genotypes. In addition, low-protein genotypes had higher straw nitrogen content than conventional protein genotypes. Under dryland conditions, total nitrogen uptake for conventional protein genotypes was almost 10 kg ha^{-1} higher than for low-protein genotypes. This suggests that the mechanism for low-protein character is two-fold. First, low-protein genotypes take up less nitrogen than conventional protein genotypes. Secondly, low-protein genotypes store more of the total nitrogen uptake in straw than conventional protein genotypes. Inversely, conventional protein lines translocate a higher proportion of total nitrogen uptake to grain compared to low-protein genotypes.
6. Conventional and low-protein genotypes differed in nitrogen harvest index (NHI) in the dryland experiment. The conventional protein genotypes had a NHI of 0.62 while low-protein lines had a NHI of 0.56. A high NHI indicates that grain nitrogen makes up a larger proportion of the total nitrogen uptake, and suggests that more nitrogen is translocated to grain as compared to a lower NHI.
7. Nitrogen had many effects on agronomic performance and grain quality in the dryland experiment. In the 2005 and 2006 Williston environments, plant height increased as nitrogen levels increased. The same trend was not found in the 2005 Minot and 2006

Richardton environments. As nitrogen rates increased, heading date was hastened in the 2005 and 2006 Williston environments, but there were no significant heading date differences among nitrogen rates in the 2005 Minot and 2006 Richardton environments. Increasing levels of nitrogen had a positive relationship with grain yield, grain protein, straw nitrogen content, and total nitrogen uptake. Grain color and nitrogen harvest index both had a negative relationship with increasing rates of nitrogen.

8. In the irrigated experiment, increasing rates of nitrogen fertilizer increased plant height. Unlike the dryland experiment, there were no significant differences found in GPC and grain yield, although both GPC and grain yield numerically increased with increasing rates of nitrogen. Grain protein concentrations for all protein and height classes, and combinations thereof were less than the 135 g kg^{-1} threshold set by buyers of malting barley.
9. Straw nitrogen content had a positive relationship with nitrogen fertilizer, regardless of protein class. Straw nitrogen content of conventional protein lines was lower than low-protein lines at all rates of nitrogen applied.

Future research needs to focus on production practices for new low-protein cultivars being developed for dryland and irrigated production in western North Dakota. Current fertilizer recommendations are written for conventional protein cultivars, and should be updated for low-protein cultivars grown under irrigated and dryland conditions.

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APPENDIX

Table A1. Average monthly temperature, monthly precipitation, and departure from thirty-year average (1971-2000) for all dryland and irrigated research locations recorded by the North Dakota Agricultural Weather Network (NDAWN).

		Temperature				Precipitation	
Environment	Month	Min	Max	Average	Departure from average	Average	Departure from average
		°C				mm	
Dryland							
2005 Minot	May	5.0	17.3	11.2	-1.5	82.8	24.9
	June	12.8	23.4	18.1	0.5	255.2	178.8
	July	14.4	27.3	20.9	0.8	47.1	-16.9
2005 Williston	May	5.1	17.6	11.3	-2.1	68.8	15.7
	June	12.5	23.9	18.2	0.0	113.5	44.5
	July	14.5	29.0	21.8	0.6	38.1	-24.1
2006 Richardton[†]	May	6.0	20.3	13.1	1.1	48.3	-8.6
	June	11.3	26.0	18.7	1.7	20.1	-70.6
	July	15.5	32.7	24.1	4.1	22.4	-33.5
2006 Williston	May	7.0	20.7	13.9	0.5	34.8	-18.3
	June	11.9	25.0	18.5	0.2	40.4	-28.7
	July	15.8	32.3	24.0	2.8	10.9	-51.3
Irrigated							
2006 Nesson Valley	May	5.6	20.6	13.1	1.0	57.7	2.5
	June	11.5	24.8	18.2	1.1	43.9	-29.7
	July	14.0	31.8	22.9	3.0	14.2	-45.0
2007 Nesson Valley	May	6.4	19.4	12.9	0.8	105.4	50.3
	June	10.7	25.4	18.1	1.0	79.5	5.8
	July	15.1	31.7	23.4	3.5	36.1	-23.1

[†]Data recorded at NDSU Dickinson Research Extension Center NDAWN site located approximately 25 miles from the Richardton location.

Table A2. Genotype means of agronomic and grain quality traits for the 2005 Minot, North Dakota dryland environment.

Genotype	Row type	Height class	Revised protein class	Heading date	Plant height	Lodging	Stem breakage	Grain yield	Grain protein	Grain color
				days after 5/31	cm	1-9	1-5	Mg ha^{-1}	g kg^{-1}	°L
Conlon	2	Conventional	Conventional	27.1	60.6	2.2‡	5.0‡	2.012	130.2	53.3
Drummond	6	Conventional	Conventional	27.1	72.3	1.2	3.5	3.758	136.9	52.9
Lacey	6	Conventional	Conventional	27.8	66.0	1.7	4.3	3.684	142.8	52.5
Legacy	6	Conventional	Conventional	27.8	67.7	1.5	4.1	3.477	142.0	52.4
Robust	6	Conventional	Conventional	27.5	68.8	1.8	4.4	3.272	141.1	53.2
Stellar-ND	6	Conventional	Conventional	27.8	69.8	1.2	3.3	3.824	140.5	52.9
Tradition	6	Conventional	Conventional	27.0	67.8	1.4	3.5	3.393	141.6	53.0
2ND20798	2	Conventional	Conventional	27.7	60.2	2.3	4.5	3.961	121.9	52.0
ND23302	6	Conventional	Conventional	27.8	66.3	1.3	4.3	3.763	127.2	50.6
ND23309	6	Conventional	Conventional	27.5	61.5	1.3	4.3	3.739	127.4	51.0
ND23283	6	Conventional	Low	27.6	70.4	1.3	2.3	3.644	111.6	50.3
ND23288	6	Conventional	Low	27.7	69.8	1.3	3.3	3.570	106.5	50.4
ND23305	6	Conventional	Low	27.6	75.6	1.3	2.4	3.710	109.8	50.5
2ND22170	2	Semidwarf	Low	27.9	52.7	1.2	2.7	4.230	123.6	51.8
ND23286	6	Semidwarf	Conventional	27.5	62.9	1.2	3.3	3.768	132.5	51.8
ND24614	6	Semidwarf	Conventional	27.4	66.9	1.3	3.9	4.110	129.2	51.4
ND24615	6	Semidwarf	Conventional	27.5	60.4	1.0	2.7	3.965	133.5	52.0
ND24616	6	Semidwarf	Conventional	27.8	58.5	1.2	1.9	3.785	133.2	51.7
ND24617	6	Semidwarf	Conventional	27.4	66.9	1.1	4.3	3.648	128.9	51.9
2ND22182	2	Semidwarf	Low	27.3	65.6	2.1	3.1	4.067	118.8	52.2
ND23285	6	Semidwarf	Conventional	27.7	59.0	1.1	2.3	3.914	130.7	51.8
ND23300	6	Semidwarf	Conventional	28.1	59.6	1.1	2.8	3.527	133.9	51.5
ND23303	6	Semidwarf	Conventional	27.9	58.3	1.2	2.3	3.703	134.3	51.2
ND23304	6	Semidwarf	Conventional	28.1	62.3	1.2	2.8	3.030	147.7	51.8
ND23310	6	Semidwarf	Conventional	28.0	60.2	1.1	2.8	3.822	132.3	51.4
%CV				1.4	4.2	32.0	14.8	5.6	2.1	0.5

‡Lodging score: 1=no lodging, 9=severe lodging. Stem breakage score: 1=no stem breakage, 5=severe stem breakage.

Table A3. Genotype means of biomass traits for the 2005 Minot, North Dakota dryland environment.

Genotype	Row type	Height class	Revised protein class	Straw nitrogen	Grain nitrogen	Harvest index	Nitrogen harvest index	Total nitrogen uptake
				g kg^{-1}	g kg^{-1}			kg ha^{-1}
Conlon	2	Conventional	Conventional	13.3	20.9	0.43	0.55	211.6
Drummond	6	Conventional	Conventional	14.0	21.7	0.46	0.57	265.5
Lacey	6	Conventional	Conventional	14.1	22.6	0.46	0.58	265.9
Legacy	6	Conventional	Conventional	14.8	22.4	0.43	0.54	238.0
Robust	6	Conventional	Conventional	12.2	22.3	0.44	0.60	227.2
Stellar-ND	6	Conventional	Conventional	11.7	22.2	0.49	0.65	244.2
Tradition	6	Conventional	Conventional	13.1	22.5	0.43	0.58	251.3
2ND20798	2	Conventional	Conventional	14.2	19.7	0.45	0.53	250.6
ND23302	6	Conventional	Conventional	14.0	20.0	0.45	0.54	223.8
ND23309	6	Conventional	Conventional	16.6	20.1	0.48	0.53	256.2
ND23283	6	Conventional	Low	16.2	17.7	0.43	0.44	239.0
ND23288	6	Conventional	Low	15.2	17.1	0.46	0.49	246.8
ND23305	6	Conventional	Low	15.9	17.8	0.39	0.42	234.1
2ND22170	2	Semidwarf	Low	14.5	19.7	0.49	0.57	227.9
ND23286	6	Semidwarf	Conventional	13.5	21.2	0.48	0.60	250.5
ND24614	6	Semidwarf	Conventional	13.1	20.9	0.50	0.59	259.7
ND24615	6	Semidwarf	Conventional	14.0	21.6	0.46	0.57	239.0
ND24616	6	Semidwarf	Conventional	16.2	21.5	0.44	0.52	244.2
ND24617	6	Semidwarf	Conventional	14.7	20.5	0.47	0.56	257.1
2ND22182	2	Semidwarf	Low	13.2	19.1	0.46	0.55	214.8
ND23285	6	Semidwarf	Conventional	14.3	21.1	0.49	0.57	258.3
ND23300	6	Semidwarf	Conventional	14.7	21.2	0.42	0.51	233.7
ND23303	6	Semidwarf	Conventional	15.5	22.0	0.44	0.53	261.2
ND23304	6	Semidwarf	Conventional	13.8	23.3	0.41	0.54	227.7
ND23310	6	Semidwarf	Conventional	15.4	21.3	0.46	0.54	264.0
%CV				12.7	2.0	4.5	7.1	12.9

Table A4. Genotype means of agronomic and grain quality traits for the 2005 Williston, North Dakota dryland environment.

Genotype	Row type	Height class	Revised protein class	Heading date	Plant height	Grain yield	Grain protein	Grain color
				days after 5/31	cm	Mg ha^{-1}	g kg^{-1}	°L
Conlon	2	Conventional	Conventional	26.1	60.4	1.952	132.8	54.4
Drummond	6	Conventional	Conventional	27.5	53.6	1.713	143.6	55.0
Lacey	6	Conventional	Conventional	27.8	52.8	2.104	136.1	54.3
Legacy	6	Conventional	Conventional	28.7	57.3	1.915	142.5	54.5
Robust	6	Conventional	Conventional	27.6	53.9	1.898	140.8	55.0
Stellar-ND	6	Conventional	Conventional	28.5	56.2	1.840	135.0	54.6
Tradition	6	Conventional	Conventional	28.0	56.3	2.031	139.4	55.5
2ND20798	2	Conventional	Conventional	28.2	56.9	1.874	138.6	53.7
ND23302	6	Conventional	Conventional	28.8	57.3	1.785	132.6	54.3
ND23309	6	Conventional	Conventional	27.2	49.8	1.933	134.8	53.7
ND23283	6	Conventional	Low	26.7	58.3	2.018	112.8	52.9
ND23288	6	Conventional	Low	28.1	55.0	1.653	115.5	52.3
ND23305	6	Conventional	Low	27.8	57.2	1.877	114.1	53.1
2ND22170	2	Semidwarf	Low	30.2	47.9	1.753	123.8	53.8
ND23286	6	Semidwarf	Conventional	26.9	50.4	1.894	132.8	54.2
ND24614	6	Semidwarf	Conventional	26.5	55.4	1.940	136.5	54.0
ND24615	6	Semidwarf	Conventional	27.9	47.7	1.840	142.9	54.2
ND24616	6	Semidwarf	Conventional	28.7	51.7	1.753	142.1	54.6
ND24617	6	Semidwarf	Conventional	27.3	51.3	1.812	142.4	54.3
2ND22182	2	Semidwarf	Low	27.7	53.2	1.982	120.7	53.7
ND23285	6	Semidwarf	Conventional	27.8	48.5	1.888	144.0	54.0
ND23300	6	Semidwarf	Conventional	29.7	47.8	1.874	140.8	53.9
ND23303	6	Semidwarf	Conventional	29.3	46.6	1.813	145.4	54.1
ND23304	6	Semidwarf	Conventional	28.3	53.3	1.868	139.4	54.4
ND23310	6	Semidwarf	Conventional	28.7	47.4	1.958	135.5	54.2
%CV				3.5	6.3	9.2	3.7	0.6

Table A5. Genotype means of biomass traits for the 2005 Williston, North Dakota dryland environment.

Genotype	Row type	Height class	Revised protein class	Straw nitrogen	Grain nitrogen	Harvest index	Nitrogen harvest index	Total nitrogen uptake
				g kg^{-1}	g kg^{-1}			kg ha^{-1}
Conlon	2	Conventional	Conventional	9.3	20.9	0.43	0.63	83.0
Drummond	6	Conventional	Conventional	8.6	22.7	0.41	0.64	75.3
Lacey	6	Conventional	Conventional	9.3	21.9	0.45	0.66	81.0
Legacy	6	Conventional	Conventional	9.4	22.5	0.43	0.64	80.9
Robust	6	Conventional	Conventional	7.8	22.7	0.45	0.71	89.0
Stellar-ND	6	Conventional	Conventional	7.9	21.1	0.44	0.68	76.2
Tradition	6	Conventional	Conventional	7.7	22.4	0.39	0.65	72.4
2ND20798	2	Conventional	Conventional	10.6	21.9	0.39	0.57	85.4
ND23302	6	Conventional	Conventional	8.8	21.1	0.40	0.62	71.6
ND23309	6	Conventional	Conventional	10.0	21.6	0.43	0.62	83.3
ND23283	6	Conventional	Low	9.7	17.9	0.42	0.58	78.1
ND23288	6	Conventional	Low	10.8	18.4	0.41	0.55	75.2
ND23305	6	Conventional	Low	10.4	17.9	0.40	0.53	73.2
2ND22170	2	Semidwarf	Low	8.9	19.1	0.41	0.60	73.0
ND23286	6	Semidwarf	Conventional	8.0	21.2	0.43	0.67	73.5
ND24614	6	Semidwarf	Conventional	6.8	21.6	0.46	0.73	79.1
ND24615	6	Semidwarf	Conventional	8.0	22.4	0.44	0.69	82.1
ND24616	6	Semidwarf	Conventional	9.5	23.0	0.40	0.62	80.0
ND24617	6	Semidwarf	Conventional	7.7	22.5	0.42	0.68	75.7
2ND22182	2	Semidwarf	Low	9.3	18.9	0.41	0.59	69.7
ND23285	6	Semidwarf	Conventional	9.5	23.1	0.42	0.64	86.9
ND23300	6	Semidwarf	Conventional	9.1	22.3	0.41	0.63	75.9
ND23303	6	Semidwarf	Conventional	8.1	22.7	0.42	0.67	78.5
ND23304	6	Semidwarf	Conventional	8.6	22.1	0.41	0.65	76.7
ND23310	6	Semidwarf	Conventional	9.0	21.8	0.41	0.64	74.1
%CV				20.5	3.5	7.0	9.3	14.0

Table A6. Genotype means of agronomic and grain quality traits for the 2006 Richardton, North Dakota dryland environment.

Genotype	Row type	Height class	Revised protein class	Heading date	Plant height	Lodging	Stem breakage	Grain yield	Grain protein	Grain color
				days after 5/31	cm	1-9	1-5	Mg ha^{-1}	g kg^{-1}	°L
Conlon	2	Conventional	Conventional	34.6	50.0	1.6‡	2.2‡	2.149	148.1	58.5
Drummond	6	Conventional	Conventional	31.6	47.2	1.1	1.0	2.272	153.4	58.9
Lacey	6	Conventional	Conventional	32.3	46.5	1.0	1.0	2.176	157.1	59.4
Legacy	6	Conventional	Conventional	35.4	45.8	1.0	1.0	2.533	159.6	58.9
Robust	6	Conventional	Conventional	31.8	51.4	1.4	1.0	2.057	152.3	59.3
Stellar-ND	6	Conventional	Conventional	33.3	42.4	1.0	1.0	2.279	162.3	58.0
Tradition	6	Conventional	Conventional	32.8	46.6	1.0	1.0	2.310	158.3	59.3
2ND20798	2	Conventional	Conventional	38.4	43.2	1.1	1.2	2.299	167.0	56.9
ND23302	6	Conventional	Conventional	32.0	48.2	1.0	1.0	1.985	145.3	58.4
ND23309	6	Conventional	Conventional	35.9	40.8	1.0	1.0	2.071	150.5	57.9
ND23283	6	Conventional	Low	30.6	49.1	1.0	1.0	2.168	140.1	58.3
ND23288	6	Conventional	Low	35.4	47.4	1.0	1.0	2.319	132.9	57.5
ND23305	6	Conventional	Low	32.8	50.5	1.0	1.0	2.197	134.6	57.7
2ND22170	2	Semidwarf	Low	38.8	39.7	1.0	1.0	2.537	147.5	56.4
ND23286	6	Semidwarf	Conventional	31.4	45.0	1.0	1.0	2.438	151.8	58.9
ND24614	6	Semidwarf	Conventional	31.7	47.1	1.2	1.0	2.317	159.9	58.0
ND24615	6	Semidwarf	Conventional	36.1	39.6	1.0	1.0	2.282	163.2	58.2
ND24616	6	Semidwarf	Conventional	35.6	41.1	1.0	1.0	2.209	161.5	57.8
ND24617	6	Semidwarf	Conventional	32.2	47.6	1.0	1.0	2.157	155.0	58.7
2ND22182	2	Semidwarf	Low	37.3	42.5	1.0	1.1	2.292	148.4	57.8
ND23285	6	Semidwarf	Conventional	34.5	42.0	1.0	1.0	1.907	155.4	58.0
ND23300	6	Semidwarf	Conventional	35.5	43.9	1.0	1.0	2.185	162.6	57.4
ND23303	6	Semidwarf	Conventional	37.3	40.5	1.0	1.0	2.246	164.1	57.5
ND23304	6	Semidwarf	Conventional	36.3	42.4	1.0	1.0	1.945	166.5	58.4
ND23310	6	Semidwarf	Conventional	34.3	42.9	1.0	1.0	2.243	153.0	58.3
%CV				4.1	5.9	19.6	11.9	25.8	4.4	0.5

‡Lodging score: 1=no lodging, 9=severe lodging. Stem breakage score: 1=no stem breakage, 5=severe stem breakage.

Table A7. Genotype means of biomass traits for the 2006 Richardton, North Dakota dryland environment.

Genotype	Row type	Height class	Revised protein class	Straw nitrogen	Grain nitrogen	Harvest index	Nitrogen harvest index	Total nitrogen uptake
				g kg^{-1}	g kg^{-1}			kg ha^{-1}
Conlon	2	Conventional	Conventional	12.4	23.4	0.42	0.58	166.8
Drummond	6	Conventional	Conventional	10.2	24.1	0.46	0.68	148.4
Lacey	6	Conventional	Conventional	12.8	24.5	0.46	0.62	169.8
Legacy	6	Conventional	Conventional	12.2	24.8	0.44	0.63	175.1
Robust	6	Conventional	Conventional	13.3	24.9	0.43	0.59	162.6
Stellar-ND	6	Conventional	Conventional	14.5	27.3	0.38	0.54	153.0
Tradition	6	Conventional	Conventional	12.1	24.7	0.45	0.63	166.5
2ND20798	2	Conventional	Conventional	13.6	26.6	0.37	0.53	138.7
ND23302	6	Conventional	Conventional	12.0	22.1	0.48	0.64	167.1
ND23309	6	Conventional	Conventional	13.5	24.8	0.43	0.59	152.7
ND23283	6	Conventional	Low	13.8	22.7	0.43	0.56	149.3
ND23288	6	Conventional	Low	17.3	21.0	0.41	0.46	152.5
ND23305	6	Conventional	Low	14.9	21.1	0.45	0.54	162.0
2ND22170	2	Semidwarf	Low	16.1	23.4	0.37	0.46	147.0
ND23286	6	Semidwarf	Conventional	13.8	23.7	0.45	0.59	156.5
ND24614	6	Semidwarf	Conventional	12.1	25.0	0.46	0.63	153.3
ND24615	6	Semidwarf	Conventional	12.2	25.8	0.45	0.64	162.2
ND24616	6	Semidwarf	Conventional	12.6	25.4	0.45	0.63	158.5
ND24617	6	Semidwarf	Conventional	11.3	24.2	0.50	0.69	185.2
2ND22182	2	Semidwarf	Low	13.4	23.4	0.40	0.54	136.2
ND23285	6	Semidwarf	Conventional	12.1	24.0	0.49	0.66	178.5
ND23300	6	Semidwarf	Conventional	12.6	25.3	0.43	0.60	145.8
ND23303	6	Semidwarf	Conventional	13.5	26.5	0.42	0.59	157.1
ND23304	6	Semidwarf	Conventional	13.1	28.0	0.41	0.60	166.7
ND23310	6	Semidwarf	Conventional	12.0	23.9	0.47	0.64	169.8
%CV				17.0	4.4	11.5	12.6	16.9

Table A8. Genotype means of agronomic and grain quality traits for the 2006 Williston, North Dakota dryland environment.

Genotype	Row type	Height class	Revised protein class	Heading date	Plant height	Grain yield	Grain protein	Grain color
				days after 5/31	cm	Mg ha^{-1}	g kg^{-1}	°L
Conlon	2	Conventional	Conventional	23.4	55.9	2.854	130.9	57.2
Drummond	6	Conventional	Conventional	25.8	56.8	2.360	142.0	57.6
Lacey	6	Conventional	Conventional	26.1	52.7	2.307	134.4	57.3
Legacy	6	Conventional	Conventional	27.8	56.1	2.480	139.5	57.7
Robust	6	Conventional	Conventional	26.3	58.8	2.566	141.8	57.7
Stellar-ND	6	Conventional	Conventional	26.3	51.3	2.298	138.1	57.2
Tradition	6	Conventional	Conventional	26.8	56.1	2.707	141.3	58.1
2ND20798	2	Conventional	Conventional	25.7	50.7	2.674	144.8	56.1
ND23302	6	Conventional	Conventional	27.4	49.8	2.140	136.7	57.2
ND23309	6	Conventional	Conventional	26.0	48.5	2.303	129.8	57.0
ND23283	6	Conventional	Low	25.0	52.8	2.264	124.4	56.3
ND23288	6	Conventional	Low	26.9	54.6	2.223	115.3	56.2
ND23305	6	Conventional	Low	29.6	62.7	1.604	133.4	56.7
2ND22170	2	Semidwarf	Low	29.6	39.8	2.196	140.8	57.5
ND23286	6	Semidwarf	Conventional	24.7	50.5	2.383	134.7	57.3
ND24614	6	Semidwarf	Conventional	25.3	57.8	2.332	140.6	56.8
ND24615	6	Semidwarf	Conventional	27.0	50.3	2.564	142.6	57.6
ND24616	6	Semidwarf	Conventional	26.6	49.4	2.437	145.7	56.9
ND24617	6	Semidwarf	Conventional	25.1	56.5	2.412	137.3	57.6
2ND22182	2	Semidwarf	Low	26.6	46.3	2.534	131.9	56.6
ND23285	6	Semidwarf	Conventional	26.1	44.9	2.374	140.3	56.7
ND23300	6	Semidwarf	Conventional	27.9	48.9	2.433	143.5	56.8
ND23303	6	Semidwarf	Conventional	28.8	45.0	2.249	147.0	56.8
ND23304	6	Semidwarf	Conventional	27.2	48.6	1.947	149.0	57.5
ND23310	6	Semidwarf	Conventional	27.0	47.7	2.340	139.2	57.1
%CV				3.1	6.0	9.1	3.2	0.5

Table A9. Genotype means of biomass traits for the 2006 Williston, North Dakota dryland environment.

Genotype	Row type	Height class	Revised protein class	Straw nitrogen	Grain nitrogen	Harvest index	Nitrogen harvest index	Total nitrogen uptake
				g kg^{-1}	g kg^{-1}			kg ha^{-1}
Conlon	2	Conventional	Conventional	8.4	20.8	0.43	0.66	118.5
Drummond	6	Conventional	Conventional	8.9	22.4	0.42	0.65	101.8
Lacey	6	Conventional	Conventional	6.8	21.3	0.44	0.71	108.1
Legacy	6	Conventional	Conventional	8.4	22.0	0.42	0.67	122.3
Robust	6	Conventional	Conventional	9.3	22.6	0.40	0.63	118.3
Stellar-ND	6	Conventional	Conventional	8.2	21.9	0.43	0.68	109.5
Tradition	6	Conventional	Conventional	7.9	22.5	0.42	0.68	123.1
2ND20798	2	Conventional	Conventional	9.6	22.9	0.38	0.60	106.5
ND23302	6	Conventional	Conventional	8.2	21.7	0.41	0.66	95.0
ND23309	6	Conventional	Conventional	9.5	20.9	0.44	0.65	106.2
ND23283	6	Conventional	Low	9.1	20.2	0.42	0.62	104.0
ND23288	6	Conventional	Low	10.5	18.2	0.42	0.57	103.2
ND23305	6	Conventional	Low	13.2	21.5	0.29	0.41	84.6
2ND22170	2	Semidwarf	Low	10.7	22.2	0.39	0.59	112.3
ND23286	6	Semidwarf	Conventional	8.9	21.2	0.42	0.64	96.9
ND24614	6	Semidwarf	Conventional	7.8	22.1	0.44	0.70	110.7
ND24615	6	Semidwarf	Conventional	8.5	22.4	0.43	0.68	111.5
ND24616	6	Semidwarf	Conventional	9.5	22.9	0.42	0.64	116.5
ND24617	6	Semidwarf	Conventional	8.7	21.9	0.44	0.68	118.2
2ND22182	2	Semidwarf	Low	10.2	20.9	0.39	0.58	105.9
ND23285	6	Semidwarf	Conventional	8.7	22.1	0.42	0.66	99.7
ND23300	6	Semidwarf	Conventional	8.3	22.9	0.43	0.68	125.0
ND23303	6	Semidwarf	Conventional	9.2	23.6	0.42	0.66	123.3
ND23304	6	Semidwarf	Conventional	9.4	23.5	0.40	0.64	104.3
ND23310	6	Semidwarf	Conventional	9.3	22.3	0.41	0.64	116.3
%CV				22.6	3.5	7.5	10.2	16.8

Table A10. Genotype means of agronomic and grain quality traits for the 2006 Nesson Valley (Ray, North Dakota) irrigated environment.

Genotype	Row type	Height class	Revised protein class	Heading date	Plant height	Grain yield	Grain protein	Grain color
				days after 5/31	cm	Mg ha^{-1}	g kg^{-1}	°L
Conlon	2	Conventional	Conventional	19.6	64.6	2.421	140.3	57.6
Drummond	6	Conventional	Conventional	22.4	72.0	3.692	146.3	58.2
Lacey	6	Conventional	Conventional	21.6	69.3	3.881	147.4	57.6
Legacy	6	Conventional	Conventional	23.6	74.8	3.636	148.1	57.6
Robust	6	Conventional	Conventional	22.8	76.3	3.785	146.3	58.5
Stellar-ND	6	Conventional	Conventional	21.8	67.0	3.209	137.2	57.4
Tradition	6	Conventional	Conventional	22.1	74.5	4.467	142.1	58.1
2ND20798	2	Conventional	Conventional	23.0	61.0	3.587	144.5	56.9
ND23302	6	Conventional	Conventional	22.8	64.4	2.627	134.1	57.5
ND23309	6	Conventional	Conventional	23.6	58.8	2.813	136.5	56.5
ND23283	6	Conventional	Low	20.3	65.7	3.719	122.0	55.6
ND23288	6	Conventional	Low	22.8	65.5	2.932	115.3	56.0
ND23305	6	Conventional	Low	23.9	67.4	2.525	122.5	55.9
2ND22170	2	Semidwarf	Low	25.8	49.8	2.707	141.7	57.8
ND23286	6	Semidwarf	Conventional	23.8	56.5	2.019	142.9	57.6
ND24614	6	Semidwarf	Conventional	21.5	68.3	3.082	145.5	57.0
ND24615	6	Semidwarf	Conventional	23.2	57.3	3.438	142.8	57.1
ND24616	6	Semidwarf	Conventional	23.9	57.2	2.853	146.9	56.6
ND24617	6	Semidwarf	Conventional	22.7	64.7	2.861	140.4	57.5
2ND22182	2	Semidwarf	Low	23.2	66.1	3.994	134.0	58.1
ND23285	6	Semidwarf	Conventional	23.5	58.6	3.498	142.6	56.9
ND23300	6	Semidwarf	Conventional	24.2	61.1	3.179	148.7	56.4
ND23303	6	Semidwarf	Conventional	24.3	59.3	2.751	151.7	56.4
ND23304	6	Semidwarf	Conventional	24.0	58.4	2.782	146.3	57.0
ND23310	6	Semidwarf	Conventional	24.7	55.6	1.983	148.1	57.2
%CV				2.3	7.0	13.7	2.7	0.6

Table A11. Genotype means of biomass traits for the 2006 Nesson Valley (Ray, North Dakota) irrigated environment.

Genotype	Row type	Height class	Revised protein class	Straw nitrogen	Grain nitrogen	Harvest index	Nitrogen harvest index	Total nitrogen uptake
				g kg^{-1}	g kg^{-1}			kg ha^{-1}
Conlon	2	Conventional	Conventional	13.5	22.7	0.44	0.57	160.2
Drummond	6	Conventional	Conventional	14.0	23.5	0.51	0.63	193.2
Lacey	6	Conventional	Conventional	14.3	23.7	0.51	0.64	204.4
Legacy	6	Conventional	Conventional	12.7	23.5	0.50	0.65	204.9
Robust	6	Conventional	Conventional	13.2	23.4	0.51	0.65	211.8
Stellar-ND	6	Conventional	Conventional	11.7	22.0	0.52	0.67	167.6
Tradition	6	Conventional	Conventional	11.7	23.4	0.52	0.69	220.1
2ND20798	2	Conventional	Conventional	13.7	23.0	0.49	0.61	194.6
ND23302	6	Conventional	Conventional	15.9	21.1	0.49	0.56	156.3
ND23309	6	Conventional	Conventional	16.6	21.8	0.52	0.59	180.7
ND23283	6	Conventional	Low	13.8	19.5	0.52	0.60	167.1
ND23288	6	Conventional	Low	16.3	18.3	0.50	0.52	174.7
ND23305	6	Conventional	Low	15.5	19.6	0.49	0.55	178.4
2ND22170	2	Semidwarf	Low	15.9	22.5	0.48	0.57	152.0
ND23286	6	Semidwarf	Conventional	13.6	22.6	0.51	0.63	150.5
ND24614	6	Semidwarf	Conventional	12.4	23.7	0.52	0.67	175.6
ND24615	6	Semidwarf	Conventional	13.9	22.8	0.54	0.67	206.2
ND24616	6	Semidwarf	Conventional	15.2	23.7	0.49	0.60	175.3
ND24617	6	Semidwarf	Conventional	12.3	22.4	0.53	0.67	162.0
2ND22182	2	Semidwarf	Low	13.8	21.2	0.49	0.60	194.5
ND23285	6	Semidwarf	Conventional	13.1	22.6	0.54	0.67	188.3
ND23300	6	Semidwarf	Conventional	15.7	23.5	0.45	0.54	189.2
ND23303	6	Semidwarf	Conventional	13.0	24.4	0.49	0.65	166.8
ND23304	6	Semidwarf	Conventional	13.0	23.3	0.52	0.66	167.5
ND23310	6	Semidwarf	Conventional	16.3	23.4	0.50	0.59	174.2
%CV				13.1	2.5	7.2	8.6	16.0

Table A12. Genotype means of agronomic and grain quality traits for the 2007 Nesson Valley (Ray, North Dakota) irrigated environment.

Genotype	Row type	Height class	Revised protein class	Heading date	Plant height	Grain yield	Grain protein	Grain color
				days after 5/31	cm	Mg ha^{-1}	g kg^{-1}	°L
Conlon	2	Conventional	Conventional	17.2	71.4	4.641	127.4	52.5
Drummond	6	Conventional	Conventional	19.3	77.6	5.615	134.7	52.7
Lacey	6	Conventional	Conventional	20.4	75.2	5.791	134.6	51.9
Legacy	6	Conventional	Conventional	21.9	79.8	6.444	130.1	52.9
Robust	6	Conventional	Conventional	22.2	80.0	5.006	138.4	53.3
Stellar-ND	6	Conventional	Conventional	21.1	70.3	4.534	130.4	52.5
Tradition	6	Conventional	Conventional	20.8	78.4	5.994	134.4	52.8
2ND20798	2	Conventional	Conventional	19.3	65.2	5.432	126.3	51.9
ND23302	6	Conventional	Conventional	20.7	73.8	4.666	111.1	51.3
ND23309	6	Conventional	Conventional	19.8	64.6	4.457	123.7	51.6
ND23283	6	Conventional	Low	17.8	76.8	5.557	108.7	50.5
ND23288	6	Conventional	Low	19.6	77.1	4.802	108.5	51.0
ND23305	6	Conventional	Low	21.8	70.4	3.915	107.4	51.4
2ND22170	2	Semidwarf	Low	20.3	63.6	4.135	112.6	52.1
ND23286	6	Semidwarf	Conventional	18.8	70.1	5.256	124.6	51.4
ND24614	6	Semidwarf	Conventional	18.5	71.6	4.742	131.6	51.1
ND24615	6	Semidwarf	Conventional	19.3	63.8	4.841	136.4	51.9
ND24616	6	Semidwarf	Conventional	20.3	61.4	4.367	138.3	51.0
ND24617	6	Semidwarf	Conventional	19.4	72.0	4.892	131.9	51.6
2ND22182	2	Semidwarf	Low	17.8	64.1	5.496	119.2	52.5
ND23285	6	Semidwarf	Conventional	19.9	63.7	4.714	135.1	51.4
ND23300	6	Semidwarf	Conventional	21.8	65.2	5.044	132.6	51.0
ND23303	6	Semidwarf	Conventional	21.5	62.3	4.929	134.9	50.6
ND23304	6	Semidwarf	Conventional	22.2	65.8	4.906	133.4	51.9
ND23310	6	Semidwarf	Conventional	20.6	64.2	4.843	126.7	51.5
%CV				3.5	5.7	6.9	1.7	0.5

Table A13. Genotype means of biomass traits for the 2007 Nesson Valley (Ray, North Dakota) irrigated environment.

Genotype	Row type	Height class	Revised protein class	Straw nitrogen	Grain nitrogen	Harvest index	Nitrogen harvest index	Total nitrogen uptake
				g kg^{-1}	g kg^{-1}			kg ha^{-1}
Conlon	2	Conventional	Conventional	10.2	20.4	0.45	0.62	140.6
Drummond	6	Conventional	Conventional	12.1	21.3	0.53	0.67	201.9
Lacey	6	Conventional	Conventional	11.0	21.3	0.54	0.70	199.3
Legacy	6	Conventional	Conventional	11.8	20.5	0.53	0.67	229.5
Robust	6	Conventional	Conventional	11.8	22.0	0.50	0.65	194.2
Stellar-ND	6	Conventional	Conventional	11.8	20.5	0.53	0.66	149.5
Tradition	6	Conventional	Conventional	14.1	21.4	0.51	0.63	224.0
2ND20798	2	Conventional	Conventional	10.5	20.1	0.52	0.67	184.2
ND23302	6	Conventional	Conventional	12.9	17.3	0.52	0.60	152.5
ND23309	6	Conventional	Conventional	12.7	19.5	0.54	0.65	153.5
ND23283	6	Conventional	Low	11.4	17.0	0.51	0.62	179.2
ND23288	6	Conventional	Low	14.6	17.2	0.52	0.57	182.6
ND23305	6	Conventional	Low	12.9	17.1	0.51	0.58	131.6
2ND22170	2	Semidwarf	Low	12.9	17.8	0.48	0.56	154.3
ND23286	6	Semidwarf	Conventional	10.8	19.5	0.54	0.68	173.4
ND24614	6	Semidwarf	Conventional	10.5	21.1	0.54	0.70	169.8
ND24615	6	Semidwarf	Conventional	11.5	21.6	0.54	0.69	166.8
ND24616	6	Semidwarf	Conventional	11.8	21.8	0.54	0.69	172.8
ND24617	6	Semidwarf	Conventional	10.7	20.9	0.53	0.69	163.4
2ND22182	2	Semidwarf	Low	11.9	19.1	0.51	0.63	173.1
ND23285	6	Semidwarf	Conventional	12.5	21.4	0.55	0.68	183.6
ND23300	6	Semidwarf	Conventional	12.5	21.0	0.54	0.66	206.4
ND23303	6	Semidwarf	Conventional	11.5	21.4	0.55	0.70	164.5
ND23304	6	Semidwarf	Conventional	11.3	21.1	0.55	0.69	167.6
ND23310	6	Semidwarf	Conventional	12.4	20.1	0.53	0.65	162.9
%CV				16.0	1.5	2.8	5.6	10.7

Table A14. Sources of variation, degrees of freedom, mean squares, results of *F*-tests, and coefficients of variation of pertinent agronomic traits from the combined analysis of variance from four dryland environments.

Sources of variation	df	Heading date	Plant height	Grain yield	Grain protein	Grain color
Environment†	3	3158.32**	16469.23**	161.50**	271.23**	2063.91**
Replicate (Env)	8	7.45*	45.37*	0.94**	4.61**	4.90**
Height class	1	107.24	8218.45**	2.90	45.83*	1.57
Env x Height class	3	32.77**	88.04**	1.35**	1.80	3.90
Protein class	1	9.31	74.93	0.27	446.23**	90.79*
Env x Protein class	3	5.92	140.36**	2.48**	5.61**	4.59
Height class x Protein class	1	0.11	158.15	3.41	20.87	55.15
Env x Height class x Protein class	3	13.71**	58.27*	0.67*	3.03*	17.93**
Error (a)	24	1.70	16.30	0.18	0.86	1.57
Nitrogen	3	112.02	987.13	7.49*	221.31**	15.52*
Env x Nitrogen	9	34.70**	409.99**	1.76**	27.44**	2.98
Error (b)	24	4.42	26.28	0.41	1.87	5.69
Height class x Nitrogen	3	0.44	1.36	0.09	0.54	0.34
Env x Height class x Nitrogen	9	1.54	14.25	0.07	0.43	0.57
Protein class x Nitrogen	3	0.14	2.16	0.11	0.43	0.32
Env x Protein class x Nitrogen	9	1.23	3.09	0.08	0.43	0.55
Height class x Protein class x Nitrogen	3	1.81	13.85	0.18	0.41	3.55
Env x Height class x Protein class x Nitrogen	9	3.12	8.27	0.15	0.28	3.78
Error (c)	1080	3.13	23.04	0.18	0.70	2.26
%CV		6.1	9.0	16.6	6.0	2.7

*, ** Significant at the ($P \leq 0.05$) and ($P \leq 0.01$) levels of probability, respectively.

†Env=Environment

Table A15. Sources of variation, degrees of freedom, mean squares, results of *F*-tests, and coefficients of variation of lodging and stem breakage traits from the combined analysis of variance from the 2005 Minot and 2006 Richardton dryland environments.

Sources of variation	df	Lodging	Stem breakage
Environment†	1	13.98**	636.88**
Replicate (Env)	4	0.95**	1.00
Height class	1	1.56	20.97
Env x Height class	1	0.29	14.46**
Protein class	1	0.29	4.10
Env x Protein class	1	0.15	1.57
Height class x Protein class	1	5.73	10.33
Env x Height class x Protein class	1	2.84**	4.54**
Error (a)	12	0.25	0.35
Nitrogen	3	0.84	3.82
Env x Nitrogen	3	0.53	4.35**
Error (b)	12	0.16	0.23
Height class x Nitrogen	3	0.05	0.47
Env x Height class x Nitrogen	3	0.06	0.49
Protein class x Nitrogen	3	0.08	0.21
Env x Protein class x Nitrogen	3	0.22	0.13
Height class x Protein class x Nitrogen	3	0.24	0.02
Env x Height class x Protein class x Nitrogen	3	0.18	0.04
Error (c)	540	0.16	0.46
%CV		33.5	30.8

*, ** Significant at the ($P \leq 0.05$) and ($P \leq 0.01$) levels of probability, respectively.

†Env=Environment

Table A16. Sources of variation, degrees of freedom, mean squares, results of *F*-tests, and coefficients of variation of pertinent biomass traits from the combined analysis of variance of four dryland environments.

Sources of variation	df	Straw nitrogen	Grain nitrogen	Harvest index	Nitrogen harvest index	Total nitrogen uptake
Environment†	3	12.602**	4.338**	0.063**	0.254**	815232.28**
Replicate (Env)	4	0.214**	0.065**	0.002	0.006	912.99
Height class	1	0.113	0.611**	0.005	0.049	221.28
Env x Height class	3	0.061	0.013	0.003	0.005	394.72
Protein class	1	2.113*	7.796**	0.014	0.497*	15108.46**
Env x Protein class	3	0.146*	0.131**	0.006*	0.016*	339.42
Height class x Protein class	1	0.442	0.225	0.001	0.025	1281.52
Env x Height class x Protein class	3	0.215*	0.056	0.016**	0.047**	867.52
Error (a)	12	0.037	0.026	0.001	0.002	1061.59
Nitrogen	3	6.280**	3.720**	0.006	0.157*	56461.03**
Env x Nitrogen	9	0.704*	0.459**	0.004	0.031	5725.04
Error (b)	12	0.247	0.041	0.003	0.013	2688.40**
Height class x Nitrogen	3	0.092*	0.018	0.001	0.001	656.28
Env x Height class x Nitrogen	9	0.017	0.011	0.001	0.003	392.14
Protein class x Nitrogen	3	0.091	0.009	0.001	0.011*	153.94
Env x Protein class x Nitrogen	9	0.027	0.006	0.001	0.002	350.19
Height class x Protein class x Nitrogen	3	0.025	0.015	0.001	0.005	473.68
Env x Height class x Protein class x Nitrogen	9	0.039	0.004	0.001	0.002	219.43
Error (c)	708	0.046	0.018	0.002	0.005	613.79
%CV		18.8	6.0	10.2	12.0	17.0

*, ** Significant at the ($P \leq 0.05$) and ($P \leq 0.01$) levels of probability, respectively.

†Env=Environment

Table A17. Sources of variation, degrees of freedom, mean squares, results of *F*-tests, and coefficients of variation of pertinent agronomic traits from the combined analysis of variance of two irrigated environments.

Sources of variation	df	Heading date	Plant height	Grain yield	Grain protein	Grain color
Environment†	1	1059.10	3970.58	286.51	208.69	2640.89
Replicate (Env)	4	5.65	754.66	9.06	2.58	1.73
Height class	1	38.75	7278.70*	2.19	60.43	20.01
Env x Height class	1	98.14**	17.45	0.04	5.81**	7.50**
Protein class	1	3.87	136.27	0.81	266.18	8.05
Env x Protein class	1	41.98**	47.16	2.84*	3.17**	0.89
Height class x Protein class	1	0.16	53.62	9.99	20.77	147.29*
Env x Height class x Protein class	1	13.55**	75.25	0.87	6.26**	0.67
Error (a)	12	0.37	16.81	0.63	0.33	0.32
Nitrogen	3	3.28	1068.80*	7.57	18.38	0.26
Env x Nitrogen	3	2.52	66.13	1.96	2.96	0.36
Error (b)	12	4.49	375.63	5.70	1.54	0.73
Height class x Nitrogen	3	0.68	16.58	0.33	0.14	0.12
Env x Height class x Nitrogen	3	0.39	36.45	0.20	0.17	0.05
Protein class x Nitrogen	3	1.26*	10.42	0.59	0.32	0.80**
Env x Protein class x Nitrogen	3	0.11	8.30	0.49	0.04	0.01
Height class x Protein class x Nitrogen	3	1.29	0.89	0.29	0.27	0.06
Env x Height class x Protein class x Nitrogen	3	0.79	6.41	0.08	0.04	0.06
Error (c)	540	2.09	40.27	0.51	0.37	0.35
%CV		6.7	9.5	17.6	4.6	1.1

*, ** Significant at the ($P \leq 0.05$) and ($P \leq 0.01$) levels of probability, respectively.

†Env=Environment

Table A18. Sources of variation, degrees of freedom, mean squares, results of *F*-tests, and coefficients of variation of pertinent biomass traits from the combined analysis of variance of two irrigated environments.

Sources of variation	df	Straw nitrogen	Grain nitrogen	Harvest index	Nitrogen harvest index	Total nitrogen uptake
Environment†	1	3.019**	3.975**	0.019**	0.047**	2909.05
Replicate (Env)	2	0.265**	0.060**	0.002	0.014**	8560.56**
Height class	1	0.058	0.995	0.000	0.018*	2328.77
Env x Height class	1	0.022	0.060*	0.000	0.000	44.98
Protein class	1	0.771	4.583*	0.018	0.289	8228.67
Env x Protein class	1	0.014	0.028	0.003	0.004	354.01
Height class x Protein class	1	0.021	0.371	0.019	0.001	1987.21
Env x Height class x Protein class	1	0.002	0.090*	0.001	0.007	83.96
Error (a)	6	0.044	0.012	0.002	0.002	1163.28
Nitrogen	3	1.037*	0.310	0.002	0.022	35104.64
Env x Nitrogen	3	0.066	0.042	0.003	0.003	7592.94
Error (b)	6	0.072	0.051	0.004	0.014	10739.02
Height class x Nitrogen	3	0.030	0.003	0.001	0.001	1221.58
Env x Height class x Nitrogen	3	0.004	0.005	0.001	0.001	166.26
Protein class x Nitrogen	3	0.047*	0.003	0.002	0.004	484.90
Env x Protein class x Nitrogen	3	0.003	0.004	0.001	0.002	1597.54
Height class x Protein class x Nitrogen	3	0.057	0.002	0.001	0.003	580.07*
Env x Height class x Protein class x Nitrogen	3	0.010	0.001	0.001	0.002	57.60
Error (c)		0.049	0.010	0.001	0.003	1021.92
%CV		17.0	4.7	6.9	8.7	18.0

*, ** Significant at the ($P \leq 0.05$) and ($P \leq 0.01$) levels of probability, respectively.

†Env=Environment