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Title: Nitrogen Management and Variety Selection for Dryland Production of Hard Red Winter Wheat in Northeastern Oregon

Abstract approved:

Michael D. Flowers

Proper nitrogen (N) management and variety selection are important for profitable hard red winter (HRW) wheat production in the dryland growing regions of northeastern Oregon. In these dryland systems, N management for grain yield and grain protein concentration (GPC) is challenging due to climatic and year-to-year variation in production environments. However, current fertilizer guides make little distinction between locations and incorporate relatively little data from HRW production. Identifying adequate N management practices and scenarios suitable for HRW production will help producers reduce risk and enhance profits. This study investigates the effects of fertilizer N rate, N application timing, variety and location over six site-years in northeastern Oregon from 2007-2009. Whole plant tissue nitrogen (TN) concentration at Zadoks growth stage (GS) 30 and flag leaf nitrogen (FLN) were also evaluated as decision making tools for N management in this region. Three sites representing low and intermediate precipitation zones were chosen for this study. A site at Pendleton, Oregon represented an intermediate precipitation zone (420 mm), while sites at Lexington and Arlington, Oregon were in a low precipitation (250-300 mm) zone. Study sites were minimally responsive to N treatments in terms of yield. Spring N was less detrimental to yield than fall application when N was excessive at Lexington and

Arlington. Grain protein concentration response to fertilizer N was significant and varied by site-year. Some site-years proved favorable for efficient production of high GPC HRW wheat, whereas acceptable GPC was very difficult to achieve in others, underscoring the difficulty of consistently producing high GPC HRW wheat in these regions. Fertilizer N use efficiency was 18-39% at Pendleton, but generally less than 20% at Lexington and Arlington, dropping to zero in some circumstances. At all sites the soil N pool was used more efficiently than fertilizer N, indicating that HRW production is best suited where only minimal fertilizer N is required to complement crop N requirements. Spring N application improved GPC one year at Pendleton following above average late spring rainfall, and may therefore be a useful N management strategy in that environment. In contrast, spring N had a neutral or negative impact on GPC at Lexington and Arlington. Overall, current recommendations did not adequately describe N requirements observed in this study. However, requirements for achieving target GPC were generally lower and more stable at Pendleton, indicating that this and similar environments may be more suitable for HRW production than low yield, high stress environments such as Lexington and Arlington. Varieties showed similar response to N treatments regardless of site. Grain yield of HRW varieties were generally competitive with the soft white winter (SWW) variety ‘Stephens’. Among tested HRW varieties, ‘Norwest 553’ expressed the best combination of yield and GPC performance. The relationship of tissue N (TN) concentration at Zadoks growth stage 30 to GPC was stable across site-years. A critical TN level of 41 g kg^{-1} corresponded to 126 g kg^{-1} GPC. This level could be used to indicate when additional N is required to achieve desired GPC, but it remains uncertain how useful this test would be at high stress, low rainfall sites considering the poor response to spring N at Lexington and Arlington. Flag leaf N also showed promise for predicting GPC, but additional research is necessary to clarify this relationship.

Nitrogen Management and Variety Selection for Dryland Production of Hard Red Winter Wheat in Northeastern Oregon

by

Daniel R. Jepsen

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APPROVED:

Major Professor, representing Crop and Soil Science

Head of the Department of Crop and Soil Science

Dean of the Graduate School

I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Daniel R. Jepsen, Author

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GENERAL INTRODUCTION

Hard red winter wheat

History of nitrogen fertilizer and wheat production in the Pacific Northwest

Nitrogen (N) is an essential element for plant growth and development of all plants. Decomposition of organic matter and fixation of atmospheric N_2 by leguminous species are two important natural sources of soil N. Nitrogen fertilizer has become an increasingly important N source for production agriculture since the discovery of the Haber-Bosch process, which permitted the large scale synthesis of fixed N.

Large quantities of fertilizer N first became available to wheat producers in Oregon following the Second World War. Fertilizer N use and the introduction of high yielding semi-dwarf wheat varieties dramatically improved crop productivity in this region. As the popularity of fertilizer N use increased, agronomists at the regional land grant universities initiated experiments with wheat to better understand the effects of fertilizer N on traits such as yield, grain protein concentration (GPC), and test weight.

Among the most extensive N fertilization studies undertaken for wheat production in Oregon were those of Hunter et al. (1961) in the 1950's and 1960's. They investigated 173 dryland wheat growing sites in northeastern Oregon, which encompassed multiple environments differing in annual precipitation, growing season length, soil type, and other characteristics. Concurrent and subsequent research throughout this and other dryland wheat growing regions of the Pacific Northwest (PNW) eventually led to establishment of N application rate and management guidelines (Gardner et al., 1975; Halvorson et al., 1972; Koehler, 1960).

These studies and contributions from other agronomists worldwide have added to our understanding of the management of N in agriculture systems. However, N management remains an imperfect science. General statements can be made regarding the behavior of N and its effect in agriculture systems, but these are greatly influenced by environment. Numerous interactions between the soil, moisture, weather patterns, management practices, and the crop itself will affect response to N.

Such interactions play a role even in relatively stable agro-ecosystems. However, the wheat growing regions of northeastern Oregon are characterized by many distinct environments. Given the complexity of unraveling these interactions, the following discussion focuses upon the primary effects of N, while also paying attention to the most pertinent environmental interactions. Furthermore, the economic context of wheat production in the Colombia Basin as it relates to N is provided as the basis of this discourse.

Importance of hard red winter wheat to grain producers

Soft white winter (SWW) wheat is the primary wheat market class produced in Oregon and the greater PNW (NASS, 2004-2009). Production of a nontraditional market class such as hard red winter (HRW) wheat has the potential to increase farm profitability. For grain delivered to Portland, Oregon, higher market value of HRW wheat is generally associated with GPC of 115-130 g kg^{-1} or greater. From 1998 to 2009 market value per Mg of 120 g kg^{-1} GPC HRW wheat at Portland has averaged $19 more than SWW wheat (figure 1.1) At times this premium has exceeded $55 per Mg, and at others has fallen to less than bids for SWW wheat.

Elevated interest in HRW production among growers has occurred at other times in the past. In 1970, an Oregon State University Wheat Task Force investigated the potential for a shift in demand for HRW and hard red spring wheat, concluding that research should address the prospect of increasing acreage of these wheat classes (OSU, 1970). During that time HRW acreage was increasing due to the recent availability of better adapted varieties and anticipation of market premiums (Thompson, 1972). However, despite the potential for increased profits, popularity waned. Since 2004, HRW wheat has never accounted for more than 5% of the approximately 1 million wheat production acres in Oregon (NASS, 2004-2009). This is due in large part to the difficulty of consistently meeting market expectations for GPC.

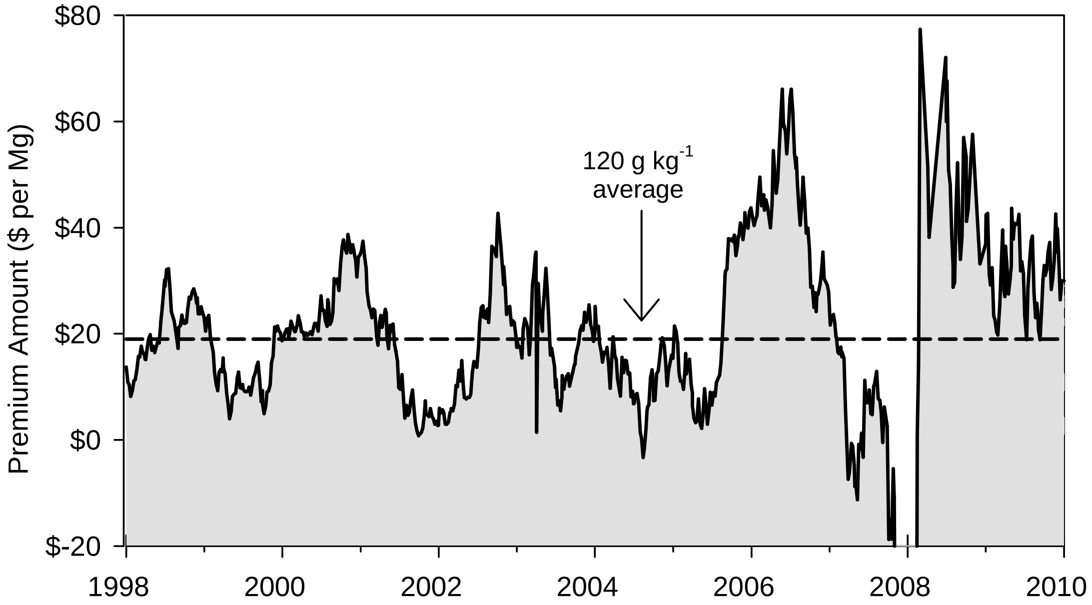

Figure 1.1 Market premiums at Portland, Oregon for 120 g kg^{-1} grain protein concentration hard red winter wheat versus soft white wheat from January 1999 to September 2009. (Source: U.S. Department of Agriculture Livestock and Seed Market News)

Proper N management is essential to produce HRW wheat that meets both grower needs for high grain yield and market expectations for high GPC. Grain protein concentration of 125 g kg^{-1} meets the quality expectations of millers and end users (PNW WQC, 2007), while capturing most of the market premium for HRW wheat. Achieving this “target” GPC requires that wheat take up N in excess of requirements for yield. Higher fertilizer N rates can elevate GPC (OSU, 1970) Environmental factors such as climate, precipitation amount and timing, and temperature during grain fill also influence GPC (Rao et al., 1993). Variation among these factors in the dryland wheat regions of northeastern Oregon may require unique N management considerations for each location and crop year.

Genotype also has a strong effect on agronomic performance, grain quality, and GPC. Therefore, variety selection is important to successful HRW wheat production. Anecdotal evidence from the Oregon State University statewide variety trials suggests that some new HRW wheat varieties have improved N use efficiency (NUE) expressed through increased GPC (Flowers et al., 2009) Further research is warranted to confirm these observations.

Breaking the yield-protein barrier

Grain yield is often negatively correlated with GPC (Costa and Kronstad, 1994; Cox et al., 1985; Terman et al., 1969). This inverse relationship is most evident when comparing low and high production environments. For example, maximum attainable GPC of HRW wheat in western Canada was 150 g kg^{-1} when produced under favorable growing conditions, but as high as 230 g kg^{-1} where terminal drought severely curtailed yield (Fowler and Brydon, 1989).

For this reason, it is believed that HRW wheat in Oregon is best suited to high stress, low yield environments (Thompson, 1972). However, research on both irrigated HRW wheat and hard red spring wheat (HRS) show that with proper N management both yield and GPC targets can be obtained in low stress, high yielding environments (Brown and Petrie, 2006; Shock et al., 1986).

The negative yield-protein relationship also applies when varieties differing for yield potential are grown under equivalent N fertility. The lowest yielding varieties generally express the highest GPC and vice versa. Combining high yield with enhanced GPC has proven a formidable challenge to wheat breeders and agronomists alike. For many years, reduced yield has been associated with HRW wheat varieties when compared to their SWW counterparts (Brown and Petrie, 2006; Shock et al., 1986). Lower yield may confer some advantages in meeting market expectation for GPC, but is generally unattractive to growers seeking to maximize production.

Plant breeders continually seek to develop varieties expressing both high grain yield and GPC. Numerous breeding approaches and germplasm screening methods have been proposed to meet this goal (Costa and Kronstad, 1994; Cox et al., 1985; Mou et al., 1994; van Sanford and MacKown, 1987). Although gains have been difficult to obtain, selection of high yield, high GPC varieties has proven possible, as evidenced by HRW varieties such as ‘Lancota’ and ‘C.I.14016’ (Cox et al., 1985; Johnson et al., 1973).

While plant breeders look for genetic avenues for GPC enhancement, agronomists have been largely successful at maintaining GPC of higher yield varieties through increased use of fertilizer N and practices that maximize nitrogen use efficiency (NUE).

General effects of nitrogen in wheat production systems

Yield components

Nitrogen acts to increase grain yield by enhancing components that contribute to yield formation. These components include: fertile tillers, spikelets per head, and kernel size. Growth and development of these structures occur at specific growth stages during the wheat life cycle. Impact on these components depends upon N availability during corresponding growth stages. Relative contribution of components may vary by year and among varieties, but always have the cumulative effect of increasing yield when N is adequately supplied (Rohde, 1963).

The first yield component to develop are tillers. Tiller number typically has the greatest influence upon grain yield (Brown and Petrie, 2006; Rohde, 1963). Given favorable growing conditions, axillary tiller formation proceeds after Zadoks growth stage (GS) 13, as the fourth leaf begins to unfold (Beuerlein, 2001a; Karow et al., 1993; Zadoks et al., 1974). Substantial tillering may occur prior to onset of winter dormancy, before stem elongation in the spring, or both (Beuerlein, 2001b).

Determination of the maximum number of kernels per head begins at the four leaf stage for each tiller and is complete at stem elongation, if not earlier (Nelson et al., 1998). Microscopic reproductive primordia are developing at this time, giving rise to spikelets. These may eventually produce anywhere from one to nine kernels each, with a mean of five. By the double ridge stage of primordial development, maximum kernel number is set. Heads may abort kernel numbers, but cannot increase this number after the double ridge stage (Cook and Veseth, 1991).

Kernel size is primarily a function of plant health and grain fill duration. Wheat plants that have adequate water and nutrient are best able to supply photosynthate and essential nutrients for growth and development of kernels. Between 750-800 growing degree days accumulate during this period of grain fill (Cook and Veseth, 1991). Therefore, lower temperatures lengthen the number of days for grain filling, which acts to maximize total kernel growth.

High N fertility promotes maximum potential of yield components. Continued N supply in subsequent growth stages is necessary to maintain this potential. Following initiation of stem elongation N deficiency can result in tiller abortion, reducing stand density at maturity (Spiertz and Vos, 1983). Aborted tillers do not contribute to yield, reducing overall plant resource use efficiency (Cook and Veseth, 1991). Nitrogen deficiency near anthesis can reduce kernel set. Kernels themselves can derive most necessary N via translocation from other plant structures, but may benefit from extended green leaf duration associated with higher post anthesis N fertility (Gregory et al., 1981; Spiertz and Vos, 1983).

The individual yield components are not independent, however. For example, high N availability may improve floret initiation, but competition among tillers may mitigate gains (Spiertz and Vos, 1983). In a similar manner, tiller competition may also reduce kernel size (Palta and Fillery, 1995). While this competition may at first seem negative, it adds plasticity to grain yield, which stabilizes production across situations of varying biotic and abiotic stress.

Physiological considerations of grain yield and protein

Wheat grain is composed of approximately 70% starch with protein, bran, and the germ comprising the remainder (Bhullar and Jenner, 1985; Jenner, 1994). Formation of grain yield, and more specifically GPC, requires an adequate supply of carbohydrate and N for developing kernels. Grain protein concentration is a product of both absolute protein content and carbohydrate deposition. Factors influencing either constituent impact both grain yield and GPC. Increasing starch deposition or reducing protein synthesis both result in lower GPC, and vice versa.

Photosynthesis during grain fill supplies kernels with energy and reduced carbon for synthesis of starch, protein and other tissues. Conditions favoring efficient photosynthesis and extended green leaf area enhance photosynthate supply, potentially improving grain yield (Spiertz and Vos, 1983), and even GPC in some circumstances (Mou et al., 1994). One gram of photosynthetically derived glucose may drive synthesis of either 0.83 grams of starch, or 0.4 grams of protein (De Vries et al., 1974). The higher energetic cost of protein synthesis suggests that any increase in GPC will reduce starch quantity and overall yield. This places a physiological constraint on combining both high yield and GPC. However, energetics do not hold exclusive influence on these variables since high yields have been obtained with varieties expressing inherently high GPC (Johnson et al., 1973).

De novo photosynthate is not the exclusive source of energy and carbon to developing kernels. Translocation of carbon assimilated during prior growth stages and stored in the stems and leaves also account for resources utilized during grain fill. Estimating translocation of stored assimilate has proven difficult and is due at least in part for want of a single, unbiased testing methodology (van Herwaarden et al., 1998b). Two available methods include: 1) use of carbon isotopes to track partitioning between vegetative biomass and grain, and 2) mass balance of pre- and post-anthesis dry matter. Use of carbon-14 tracers to estimate assimilate contribution to yield indicated that this source supplied 12% and 22% of final yield for irrigated and water stressed wheat, respectively (Bidinger et al., 1977). Results were 37% and 97%, respectively, for this same comparison using a mass balance approach, although the author noted several sources of error associated with this method (van Herwaarden et al., 1998a). Despite differing values, both approaches demonstrate that grain from terminally drought stressed wheat derives a greater portion of yield from stored assimilate.

While carbon from stems and leaves accounts for at least some portion of starch in grain, translocation of nitrogenous compounds supplies the majority of grain N. Between 50% and 95% of grain N may be derived from N previously assimilated into vegetative biomass (van Sanford and MacKown, 1987; Xu et al., 2006). On average, 65-80% of grain N at maturity is already present in aboveground plant matter at anthesis, with translocation from roots contributing possibly 10% (Spiertz and Vos, 1983). Continued uptake from soil during grain fill provides the remainder of grain N. Late season N uptake does not appear to significantly impact translocation efficiency of previously assimilated N (Wuest and Cassman, 1992a).

Nitrogen uptake and utilization

From germination to maturity, wheat passes through a number of discrete growth stages. Acquisition of N begins at root establishment and proceeds in subsequent growth stages, even up to the second half of grain fill (Finney et al., 1957). Figure 1.2 illustrates the general timing of N uptake by wheat. Relatively little N uptake occurs from germination to winter dormancy, at most amounting to 33.7 kg N ha^{-1} (Pumphrey and Rasmussen, 1982). Although limited N uptake occurs during the fall, the root system develops sufficiently to support rapid uptake during spring. The start of stem elongation (GS 30) marks the beginning of rapid N uptake, which persists through late booting (GS 49). Daily uptake at this time may be as high as 3.4 kg N ha^{-1} (Sullivan et al., 1999).

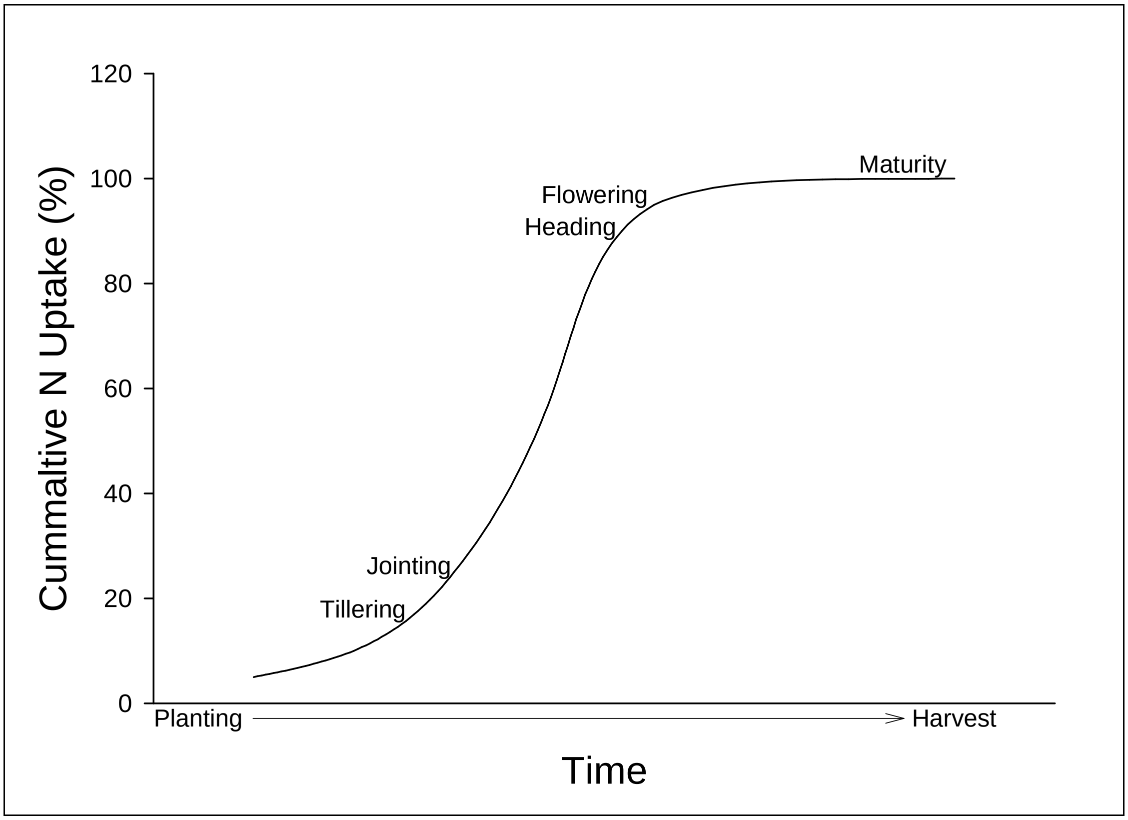

Figure 1.2 Standard nitrogen (N) accumulation pattern of wheat from planting to harvest (Source: Flowers et al., 2007)

Addition of fertilizer N may increase uptake at any of the growth stages just discussed. Greatest N accumulation occurs when N availability coincides with periods of greatest uptake from stem elongation to boot stage. Substantial N uptake may also occur following anthesis (GS 60). This represents a deviation from the uptake pattern indicated in figure 1.2. Post-anthesis uptake is minimal except where N and soil moisture levels are favorable for their continued acquisition (Wuest and Cassman, 1992b). Total post-anthesis N accumulation may account for as little as 7% or as much as 52% of aboveground plant N at maturity (Gregory et al., 1981; Loffler et al., 1985). Both scenarios were illustrated by Wuest and Cassman (1992a). They found that irrigated spring wheat supplied with additional N at anthesis acquired 30-50% of total N between anthesis and maturity. In contrast, plots receiving only preplant N acquired just 12-18% of total N during this same time.

When N availability corresponds to periods of rapid uptake, grain yield and GPC respond to increasing N in a predictable manner as illustrated in figure 1.3. The first third of this response curve, sometimes referred to as the “lag phase” (Fowler, 2003), corresponds to the first increases of N availability over that necessary to sustain minimum plant growth. Small increases of N at this level improve grain yield, but GPC remains low. Many researchers actually observe a drop in GPC with the first increment of fertilizer N (Fowler, 2003; Terman et al., 1969). The absolute quantity of grain protein actually increases in this scenario, but starch accumulation can be proportionately higher than protein deposition at lower levels of available N, resulting in GPC dilution. The lag phase may cover a wide range of N availability in high yield scenarios, but often disappears completely where environmental conditions severely constrain yield (Fowler, 2003).

Following the lag phase, both grain yield and GPC increase simultaneously given additional N. Grain yield will continue to increase in this manner until factors other than N (i.e., variety, water deficiency, disease) become limiting, at which point yield response to N plateaus. Positive GPC response continues, even as yield reaches its asymptote. As GPC increases, N may actually reduce yield.

Nitrogen use efficiency

Economic production of HRW wheat requires efficient use of N resources. Nitrogen use efficiency (NUE) describes the general efficacy of N resources for improving crop performance. Numerous approaches have been taken to define NUE. In its most

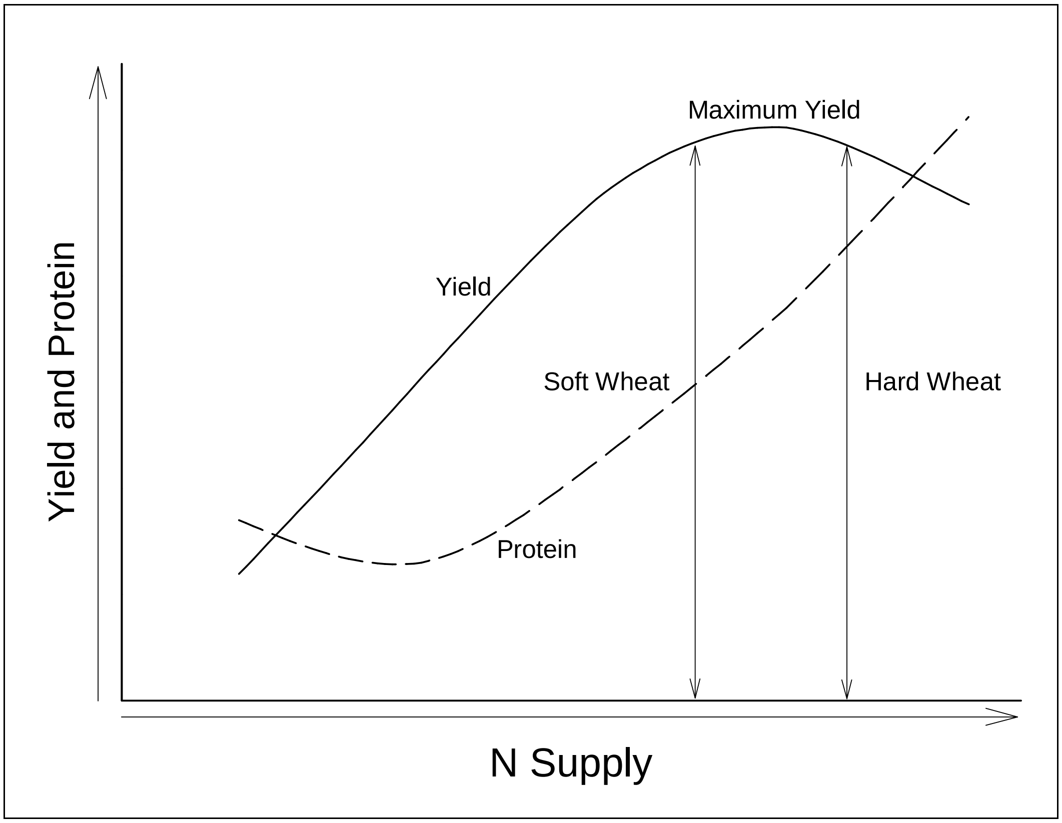

Figure 1.3 Generalized relationship between yield, grain protein concentration, and nitrogen (N) supply (Source: Flowers et al., 2007)

simple form, NUE refers to the quantity of grain produced per unit of available N (Moll et al., 1982). This definition is useful for SWW wheat production, which emphasizes high yield and low grain N. Alternatively, Raun and Johnson (1999) defined NUE in terms of total N recovery, using the equations:

NUE = [(total cereal N removed) – (N coming from the soil + N deposited in the rainfall)/ (fertilizer N applied to cereals)]

This calculation is more functional for HRW wheat production as it emphasizes grain N accumulation. Neither index, however, specifies which variables most influence efficiency, such as fertilizer vs. soil N uptake efficiency and N partitioning between grain and vegetative matter.

Many simplified fertility models, such as those found in fertilizer guides, assume equal availability of both fertilizer and soil N pools. Understanding how management practices influence recovery from these two pools and additional N dynamics is useful for improving NUE (Huggins and Pan, 1993). An ideal system would be characterized by very high percent N recovery from all N pools. When N supply is inadequate for optimum yield, as much as 80% of N may be recovered in the grain alone (Fowler et al., 1990). As available N increases, plant uptake capacity eventually becomes saturated, at which point there is no recovery of additional N (Fowler et al., 1990). An exception to this rule may occur when soil N levels are very low in the upper soil profile nearest the seed, in which case increased root proliferation due to fertilizer N improves uptake from the soil N pool (Jenkinson et al., 1985) Overall, to achieve high NUE producers must either avoid over-fertilization, identify means of increasing uptake efficiency, or both.

The ability of wheat plants to use N resources for grain protein synthesis also influences NUE. The relative partitioning of N between vegetative biomass and grain is referred to as the nitrogen harvest index (*NHI = grain N/total above ground N*). Nitrogen harvest index is often greatest when N is limiting to yield, declining as available N increase (Sticksel, 1999; Wuest and Cassman, 1992a). Nitrogen partitioning also differs between main stems and tillers (Sticksel, 1999; van Sanford and MacKown, 1987). Tiller NHI of winter wheat in Belgium was 2.8% lower than that of main stems (Sticksel, 1999). Lower grain yield of tillers resulted in slightly higher GPC in spite of lower NHI. Very high levels of N remained in straw of non ear-bearing tillers. Consequently, late season attrition of tillers results in lower whole plant NHI, and inefficient N use for grain protein synthesis.

Both N recovery and NHI may be improved where fertilization emphasizes a more consistent N supply throughout the growing season (Spiertz and Vos, 1983; Sticksel, 1999; Wuest and Cassman, 1992a). Poor overall NUE was observed for large preplant N applications in irrigated HRW and HRS wheat in at least two studies (Brown and Petrie, 2006; Wuest and Cassman, 1992b). Wuest and Cassman (1992b) also determined a NHI of 0.89 for N acquired post anthesis in spring wheat, versus a NHI of 0.7 for N assimilated at earlier growth stages

Relatively few references describe variety differences for NHI and N uptake efficiency. In studies that do examine variety differences, the results are inconclusive. For example, van Sanford and MacKown (1987) studied N uptake and NHI of nine soft red winter wheat varieties, finding that variation of N uptake was largely responsible for differences in spike N, while NHI played an insignificant role. However, when duplicate experiments were performed under controlled greenhouse conditions, N uptake differences among varieties were no longer distinguishable. While such observations do not rule out the possibility of significant genetic influence on NHI and N uptake, evidence suggests that in most scenarios N availability and other environmental factors play a more pivotal role in determining NUE for both grain yield and GPC.

Environmental and other considerations for nitrogen management

Nitrogen and water relations

Water is the primary yield determining factor for dryland production systems in semi-arid environments, such as those of northeastern Oregon. Plant available N is typically the second most limiting factor. Water and N do not behave independently. Impact of one is intimately related to the availability of the other because nitrate, the predominant mineral N form in most agriculture soils, moves primarily via mass flow.

Where moisture is the primary determinant of yield potential there exists a predictable relation between plant available water and grain yield. Approximately 5.9 cm available moisture are necessary to complete vegetative growth with modern semi-dwarf wheat varieties after which each additional centimeter of stored soil moisture increases yield 140-150 kg ha^{-1} (Leggett, 1959; Schillinger et al., 2008). Under more favorable growing conditions a coefficient of 191 kg ha^{-1} for each centimeter of available moisture has been reported (Koehler, 1960). Schillinger et al. (2008) also emphasized that yield response to spring rains differed from that to stored soil moisture, in which case April rains proved less influential on yield, while precipitation had an increasingly greater impact on yield through May and June in east central Washington.

Sufficient N is required for efficient water use. When N deficiency severely limits grain yield a considerable amount of water may remain in the soil at maturity (Cochran et al., 1978; Koehler, 1960; Leggett, 1959). Addition of fertilizer N can improve water use efficiency by enabling plant and roots to utilize available moisture. Increased N supply, even when not sufficient to completely maximize yield, generally enables the extraction of all available water from the soil profile (Cochran et al., 1978; Daigger and Sander, 1976). When N deficiency does occur, residual water is concentrated at lower soil depths (Koehler, 1960).

Water use efficiency may actually decline if N levels are too high. This can occur via several mechanisms. Yield loss from excessive N in high yield scenarios is generally attributed to lodging, but may owe to a reduction in water-soluble carbohydrates where lodging is not a factor (Brown and Petrie, 2006; van Herwaarden et al., 1998b). In low moisture situations, excessive N promotes lush vegetative growth which can result in premature depletion of soil moisture (McDonald, 1989; van Herwaarden et al., 1998a). In cases of terminal drought this leads to 'haying-off', and results in significant yield reduction.

In the same way that proper N fertility improves water use efficiency, adequate moisture availability throughout the growing season improves NUE. This tendency is part of complex ecological processes whose net result is to increase the soils' ability to supply N. Soil-plant N resiliency is a term that has been used to describe these phenomena (Meisinger et al., 2008). Adequate soil moisture contributes to this resiliency for at least two reasons; 1) warm, moist soils are conducive to the soil microbial activity required for mineralization of the organic N pool, and 2) mass flow is primarily responsible for N delivery to roots. Healthy plants in moist soil transpire more, which draws additional mineral N to root surfaces. This excludes scenarios where excess moisture results in leaching or denitrification. Without sufficient moisture to support mass flow, N may become stranded in dry soil (Fowler and Brydon, 1989; Sowers, 1994).

Positional availability of nitrogen

Nitrogen concentration in soil varies with depth. Greatest concentrations often occur in the top 30 cm where higher organic matter in the A horizon leads to greater N mineralization. Nitrogen applied as fertilizer is also found, as least initially, in this zone. Water movement may move N lower in the profile.

In semi-arid environments where precipitation is typically insufficient to completely leach fertilizer N, considerable amounts may accumulate in deeper soil. Root proliferation to 120 cm occurs prior to rapid N uptake in the spring when the majority of vegetative growth occurs (Kmoch et al., 1957). Therefore winter wheat can extract significant quantities of N from lower depths. Nitrogen placement at 150 cm depth in a Nebraska study produced similar dry matter yields as near surface placement (Daigger and Sander, 1976). However, availability of deep N (> 120 cm) is more frequently associated with late season N uptake for GPC enhancement. Several factors influence whether deep N sources are utilized; the foremost being soil moisture, as discussed previously in 'Nitrogen and water relations.' In general, if roots scavenge resources below this depth, they do so later in the season after exhausting either moisture or N higher in the profile.

Several additional studies have demonstrated the importance of N depth in relation to soil moisture. In a three year study by Cochran et al. (1978), irrigation and subsequent winter rains moved fall applied N to at least 90 cm all years. In one year when dry spring conditions prevailed, root activity moved progressively deeper to access subsoil moisture. As a result, significant late season N uptake occurred in fall applied N treatments. Grain protein concentration was 36 g kg^{-1} greater for fall N treatments than for spring applications. In addition, the spring N applications had the highest concentrations of N in the topsoil.

In the remaining two years of studies by Cochran et al (1978), the inverse occurred. Substantial spring rains maintained moisture in upper soil layers, and N mineralization in topsoil was apparently sufficient to supply N needs for yield. Consequently, late season uptake of fall applied N was insignificant, and did not confer a GPC advantage. Where late season soil moisture coincides with even less N, the resulting yield increase can have a diluting effect and reduce GPC (Smika and Greb, 1973; Wuest and Cassman, 1992b).

Prevailing water and N spatial relationships are ultimately influenced by climate. The PNW is characterized by a Mediterranean climate, in which most rainfall occurs during winter months, followed by dry summers. Soil moisture stored during the winter is crucial to production, and moisture depletion progresses from the surface downward. If N remains in the topsoil, it may potentially become stranded as soils dry, which was observed both in the PNW and in Alberta, Canada (Fowler and Brydon, 1989; Sowers, 1994). Stranded N may also have explained lower GPC associated with spring applications observed at some locations by Hunter et al. (1961). Given this scenario, and the potentially greater availability of fall applied N for GPC enhancement in these environments, fall application currently used in northeastern Oregon may already suit HRW wheat production as it allows for deeper incorporation of fertilizer by winter rains. However, existing research in this region is insufficient to move beyond mere speculation on this topic.

An exception to this rule may apply when significant rainfall occurs near or during grain fill. Such rainfall events are uncommon in northeastern Oregon, but can dramatically increase yield when they occur. Producers have expressed frustration over low GPC of HRW wheat following these rainfall events. These observations are validated by research experience in the central Great Plains, where across 55 site-years, GPC never exceeded 123 g kg^{-1} when rainfall exceeded 4.8 cm during a 15 day period between early boot and awn emergence (GS 38-45; Smika and Greb, 1973). Presumably, N taken up at these times is insufficient to maintain GPC. Moisture is rapidly wicked up by plant roots, and the wetting front may never reach fall applied N. Spring applied N could possibly be more available in such circumstances. No known research has specifically addressed these issues in northeastern Oregon.

Temperature and moisture during grain fill

Temperature during grain fill directly influences both N and carbohydrate deposition in the grain. It is well established that shortening of the grain fill period occurs with increasing temperature (Gallagher et al., 1975; Panozzo and Eagles, 1999; Wiegand and Cuellar, 1981). Maximum grain fill duration occurs at or below 15-18º C. Temperatures above this baseline result in predictable shortening of grain fill. Methods employed to quantify the temperature effect on grain fill have been inconsistent. Nonetheless, the majority of relevant publications report a shortening of 2.4 to 3.1 days per 1°C rise in average daily temperature (Wiegand and Cuellar, 1981).

Shortened grain fill duration can reduce kernel weight, which can result from high temperatures that accelerate the life cycle of wheat. Wheat possesses some plasticity in this regard. Slight temperature increases will reduce grain fill duration, but are mostly compensated by increased fill rate (Jenner, 1994). At higher temperatures, however, further grain fill rate increase is minimal and fails to compensate for further shortening of this period. A grain weight reduction of over 50% occurred with temperatures of 30° C day/25° C night in comparison to temperatures of 18 ° C day/13° C nighttime for wheat grown in a phytotron (Sofield et al., 1977). This relative lack of plasticity in starch deposition at high temperatures has been attributed in part to the inefficiency of the Starch Synthase enzyme at temperatures exceeding 30° C (Jenner, 1994).

Impaired starch deposition reduces the potential for dilution of GPC. Therefore, yield reduction induced by high temperature is generally accompanied by increased GPC. Smika and Greb (1973) reported a positive curvilinear relationship between maximum daily air temperature and GPC during the last 15 days of growth up to 32° C, after which further temperature elevation became detrimental to GPC. Positive correlation between soil temperature at the crown and GPC was also observed. Soil temperatures will generally track closely with air temperature, except where thick surface mulches shade and insulate soil.

Drought stress tends to have the same effect as high temperatures. Both stresses are reciprocal. Heat accelerates drought, and water stressed plants tend to be warmer due to reduced evapotranspirative cooling. This was demonstrated in adjacent trials of irrigated and dryland wheat in which mean grain fill was 7 days shorter in dryland treatments in one season, but only 4 days shorter the following year when late season rainfall occurred (Panozzo and Eagles, 1999). Additionally, grain N was nearly identical in both treatments, resulting in higher GPC for the dryland plots. In this case, post-anthesis N uptake was clearly minimal regardless of water regime, in which case starch deposition as a function of grain fill duration primarily determined GPC.

As a result of these environmental impacts upon grain yield and GPC, producing high GPC grain has traditionally been relegated to climates where high temperatures or other environmental factors limit starch dilution of GPC. The Great Plains of the United States experience such a climate, and have therefore been the traditional source of high GPC hard wheat. In the absence of such harsh conditions during grain fill, consistent production of high GPC HRW wheat may be difficult. In northeastern Oregon, daytime temperatures may exceed 30° C, but nighttime temperatures are rather cool (Petrie and Frank, 2004), helping prolong grain fill. This scenario is ideal for soft white production, but most certainly exacerbates the difficulty of achieving desired levels of GPC.

Nitrogen fertilization for yield and grain protein concentration

Yield

While many variables affect grain yield, N fertility is usually the most influential factor that producers can control. Therefore, it is important to apply an adequate rate of fertilizer N. Various approaches exist for determining proper fertilizer N rates. Spiertz and De Vos (1983) described a simple Dutch approach in which the sum of mineral N in a 90 cm profile and fertilizer N should equal 140 kg N ha^{-1}. In Midwestern states, some N recommendations are based upon soil type and the previous crop (Meisinger et al., 2008).

Oregon State University fertilizer guides use a yield based approach. Nitrogen needs are expressed as the ratio of N required per unit grain production at a desired GPC (table 1.1). Fertilizer N needs are equal to the product of this ratio and anticipated grain yield minus soil inorganic N in the top 120 cm and expected in-season mineralization. For example, a producer following these recommendations and anticipating yield of 5.0 Mg ha^{-1} with desired GPC of 120 g kg^{-1} would need to assure N availability between 215 and 265 kg N ha^{-1}. If soil N in the top 120 cm totals 80 kg N ha^{-1} with expected mineralization of 23 kg N ha^{-1}, the producer must supply an additional 112 to 162 kg N ha^{-1} as fertilizer.

Projected yield in this calculation may be determined using a number of criteria, including moisture-yield relations described by various researchers (Koehler, 1960; Leggett, 1959; Schillinger et al., 2008). In practice, historical farm yield and producer experience provide reasonable estimates of future yield. However, actual yield may deviate substantially from predictions depending upon growing season weather. In such cases fertilizer N rates are not suited to actual yield potential.

Accurately predicting N mineralization is also challenging. Fertilizer guides currently suggest a mineralization credit of 17-28 kg ha^{-1} if sampling in the spring of a fallow year but suggest no such credit if samples are taken within six weeks of fall planting (Lutcher et al., 2007). Research publications regarding crop season mineralization are lacking. One exception is a recent study evaluating mineralization in an eastern Oregon sandy loam soil planted to spring wheat. In the first year of this study, approximately 50 kg N ha^{-1} were mineralized from seeding to harvest (Albrecht and Long, 2008). Further research is warranted to increase the usefulness of mineralization credits suggested in Oregon State University fertilizer guides.

Table 1.1 Current Oregon State University nitrogen recommendations per unit grain production (kg Mg^{-1}) at corresponding grain protein concentration goals (g kg^{-1})

Protein Goal	Nitrogen Requirement	Average
90	33 - 40	37
100	37 - 43	40
110	40 - 48	45
120	43 - 53	50
130	47 - 58	55

Source: Lutcher et al. (2007)

Grain protein concentration targets help producers tailor N application rates to their needs. Protein target based N recommendations address not only the need to meet market expectation for grain quality, but also inherent differences in GPC among wheat classes. For example, SWW wheat fertilized for maximum yield in northeastern Oregon will have a GPC of 83-100 g kg^{-1} GPC (Glenn et al., 1985; Lutcher et al., 2007). Lesser or greater GPC can indicate over or under-fertilization of N for yield of SWW wheat, respectively, provided other nutrients are not limiting.

Similar metrics have not been described for HRW wheat in northeastern Oregon. In one of the few published examples from the PNW, Brown et al. 2006 reported N sufficiency for yield between 108 and 113 g kg^{-1} GPC for irrigated HRW wheat. Reports from HRW wheat production regions in the central Great Plains indicate N sufficiency at 115 g kg^{-1} (Smika and Greb, 1973). Meanwhile, under average to good growing conditions, sufficiency corresponded to GPC of 130 g kg^{-1} in Saskatchewan, Canada. (Fowler, 2003).

Use of GPC as a post-harvest index of N sufficiency for yield may also be influenced by yield potential itself. Fowler (2003) calculated that in Saskatchewan, Canada, GPC decreased 10 g kg^{-1} for every 0.33 Mg ha^{-1} increase in yield potential of winter wheat. Wheat yield potential varies substantially among regions in northeastern Oregon from less than 2 Mg ha^{-1} in the lowest rainfall zones, to more than 6.7 Mg ha^{-1} in others. As a result, optimum yield may correspond to slightly different GPC targets depending on production region.

Provided that GPC at optimum yield of HRW wheat in northeastern Oregon could be determined, current recommendations may still prove inadequate. Nitrogen ratios for higher GPC (>110 g kg^{-1}) given in table 1.1 were derived primarily from N uptake studies with HRS wheat. Given the longer growing season and higher yield potential of HRW wheat, one may reasonably assume that N requirements for HRW wheat production could deviate from these recommendations.

Timing of fertilizer application can also significantly influence yield. Appropriate N management aims to supply the growing wheat plant with sufficient N during critical periods of growth and development while limiting N losses to the environment. Application timing strategies employed in a given region correspond to the environmental conditions and predominant cultural practices. Wheat producers in northeastern Oregon routinely apply all fertilizer in the spring of the fallow season, or banded near the seed at fall planting. Frequency of this latter approach has increased with the growing adoption of chemical fallow and direct seeding methods. However, there is some use of banding even in conventional tillage systems.

Alternatives to preplant or seed-banded N applications include delaying part or all fertilizer N applications until just prior to stem elongation. Depending upon climate and prevailing weather conditions, delayed application may take place in either late winter, or early spring. For simplicity, both will hereafter be referred to as “spring” applications.

An extensive study in northeastern Oregon by Hunter et al. (1961) showed that for 91 of 152 sites, there were no was no yield difference between spring and fall N application. However, among remaining sites in the study, spring N produced higher yield at 42 of these and was related to soil depth and moisture. In general, where soil moisture was adequate to support the crop through to maturity, fall N was more effective at improving yield than spring N in shallow soils (<150 cm), but also caused the greatest yield losses at sites where average annual precipitation was less than 380 mm. It was presumed that spring N was less apt to over-stimulate vegetative growth which can prematurely exhaust limited soil moisture, a scenario also described by other researchers (Fowler and Brydon, 1989; McDonald, 1989). Sites with average annual precipitation greater than 380 mm were less represented in the study and deserve further consideration.

In contrast to arid environments, applying part or all N in the spring prior to stem elongation is routine in many humid environments such as the Mid-Atlantic States and areas with high winter rainfall such as western Oregon (Hart et al., 2009; Kratochvil, 2005). Spring N application produces equal or greater yield than fall N application in such environments (Doll, 1962; Welch et al., 1966). With greater precipitation, significant N losses from leaching and denitrification can occur, reducing N availability during the period of rapid uptake between stem elongation and the end of booting. Application immediately prior to stem elongation improves N fertility in the root zone during rapid uptake while avoiding potential leaching from winter rain (Doll, 1962).

Addition of N between jointing and boot stage may increase yield in some circumstances. Kratochvil et al. (2005) reported yield increases when 17 kg N ha^{-1} was applied at flag leaf emergence in addition to 68 kg N ha^{-1} applied at stem elongation.

Applying 56 kg N ha^{-1} between heading and anthesis improved yield of HRW wheat in southern Idaho in two of three years (Brown and Petrie, 2006). Grain yield increases from these late season applications suggests that N was limiting at earlier growth stages. This condition does not preclude circumstances where N losses may occur during stem elongation (Wuest and Cassman, 1992b). Improved kernel weight explains yield increases where such responses to late application occur (Sticksel, 1999; Wuest and Cassman, 1992b).

Protein

Once N needs for grain yield are satisfied, additional N elevates GPC. Current recommendations suggest an additional 7 kg N Mg^{-1} above requirements for yield in order to meet market expectations for GPC (Brown et al., 2005; Flowers et al., 2007). Additional fertilizer N may not be necessary where GPC at maximum yield already meets or exceeds market expectation. Likewise, more than 7 kg N Mg^{-1} may be required to meet GPC goals in situations with poor NUE.

Timing of N can significantly impact the efficacy of fertilizer N treatments for GPC enhancement. Grain protein concentration is frequently improved where fertilization emphasizes N application shortly before stem elongation. Spring versus fall N application resulted in similar yield, but 8–13 g kg^{-1} greater GPC for irrigated HRW wheat in southern Idaho (Brown and Petrie, 2006). Studies of N rate and timing in eastern Colorado demonstrated improvement of both yield and GPC with spring application, in which 4 and 35% more fall applied N was necessary to achieve the same GPC with spring application of 22 and 67 kg N ha^{-1}, respectively (Vaughan, 1990). Hunter et al. (1961) however, observed a general trend for lower GPC with spring N application in northeastern Oregon, despite grain yields that were equal to preplant N application. Little additional research addresses the efficacy of spring N applications for GPC enhancement in this region.

Grain protein concentration responds positively to additional N applied during stem elongation and later growth stages. Rate and timing studies by Kratochvil et al. (2005) demonstrated GPC increased with application of 17 kg N ha^{-1} at either GS 37, 50, or both in experiments with HRW wheat grown in Maryland. Between stem elongation and maturity, increasing available N has a progressively greater impact on GPC, and a declining influence on grain yield. Even small changes in fertilization timing during stem elongation may impact GPC, as suggested by Sticksel et al. (1991), who observed a tendency for higher GPC when a portion of total N was applied at GS 32 versus GS 30. Application of N from boot stage through head emergence is the latest time at which a yield increase may occur under most circumstances. However, delaying application until near anthesis or later can dramatically elevate GPC. Researchers have observed greatest GPC for N fertilization from anthesis to the watery milk stage of kernel development (Bly and Woodard, 2003; Brown and Petrie, 2006; Brown et al., 2005; Finney et al., 1957; Wuest and Cassman, 1992b). In high production environments, where rainfall and/or irrigation permit maximum yield expression, acceptable GPC may not be possible without late season N. Irrigated HRW wheat in southern Idaho exceeded 120 g kg^{-1} GPC only with additional N applied at anthesis, or when excessive fall applied N reduced yield (Brown and Petrie, 2006). Likewise, irrigated HRS wheat in the central valley of California never exceeded 120 g kg^{-1} without additional N near anthesis, even when early season N exceeded requirements for yield (Wuest and Cassman, 1992b). Late application N was incorporated with basin irrigation in both experiments.

Delivery of N through foliar application of concentrated liquid solutions of N offers an alternative to topdressing with dry granular fertilizer. Foliar application at anthesis have shown the greatest capacity to improve GPC (Bly and Woodard, 2003; Finney et al., 1957). Grain protein concentration was increased 42 g kg^{-1} to 150 g kg^{-1} compared to the control by a single foliar application of 56 kg N hg^{-1} at anthesis to HRW wheat yielding 2.0 Mg ha^{-1} (Finney et al., 1957). In this same experiment, even a more modest application of 34 kg N ha^{-1} increased GPC to 133 g kg^{-1}, well above that necessary to obtain market premiums. Efficacy of foliar sprays for GPC enhancement has been well recognized by subsequent researchers, and the practice finds acceptance in commercial production (Bly and Woodard, 2003; Woolfolk et al., 2002).

Foliar sprays are of particular interest in dryland production, where rainfall cannot be relied upon to incorporate granular topdress N. Leaf burn is a potential adverse effect of foliar application. Grain yield and test weight reductions have been reported due to leaf burn, but were not always statistically significant (Woolfolk et al., 2002). Leaf damage may be ameliorated by applying only when temperatures do not exceed 14° C (Lutcher and Mahler, 1988). Timely application of foliar N must also be emphasized, as GPC becomes asymptotic to additional foliar N in as little as 10-12 days post anthesis (Finney et al., 1957).

While the GPC enhancing benefits of N applied at anthesis are well documented, reports of how prior N applications influence their efficacy are inconsistent. Bly and Woodard (2003) found foliar N applied at GS 71-73 increased GPC most frequently when grain yield exceeded expectations. In their trials, N additions at anthesis improved GPC in only 23% of plots not exceeding yield expectations, but did so in 70% of plots where yield was greater than anticipated. Their research suggests that application at anthesis is only warranted when better than average growing conditions persist following primary N applications. In contrast, Finney et al (1957) observed GPC enhancement with foliar N at anthesis regardless of whether N applied earlier was adequate to maximize yield.

Prognostic tools for nitrogen management

Producers desire to know whether fertilizer and soil N resources are sufficient to meet crop demand for yield and GPC. Considerable uncertainty surrounds this matter, particularly since unforeseen weather patterns after planting can drastically alter both crop performance and N dynamics. This is especially the case in humid environments, where leaching and denitrification during winter months may significantly impact N availability (Weisz et al., 2007). In more arid environments, higher than expected winter rainfall may boost crop yield potential such that available N no longer satisfies demand for yield, target GPC, or both.

Spring soil sampling can provide some estimate of actual N availability and has been used successfully in regression equations to predict fertilizer needs. However, results may be confounding or difficult to interpret where plants have already extracted significant amounts of N. In such cases N may be sufficient despite low soil test N. Plant tissue tests such as N uptake and whole plant tissue N (TN) concentration are alternative measurements of N sufficiency. In theory, N uptake and TN reflect the capacity of soil to supply N and may be better indicators of N sufficiency.

The predictive ability of plant samples depends upon the collection at sampling. Vaughan et al. (1990) found whole plant N at GS 32 was best correlated with yield. Very early TN at mid-tillering provided less ability to resolve differences between N treatments in experiments by Engle and Zubriski (1982), but differences were well resolved at GS 30. Where TN is used for production purposes, samples are typically taken at GS 30, as this represents a compromise between best predictive ability and allowing enough time for lab analysis and topdressing (Bundy and Andraski, 2004). The general procedure involves removal of all above ground biomass from a known area, drying, weighing, and analysis of total N concentration. Some researchers have evaluated stem nitrate rather than TN concentration, but results are more variable than TN and less correlated with yield (Roth et al., 1989; Vaughan et al., 1990).

A linear relationship between fertilizer N rate for optimum yield and TN at GS 30 has been described for soft red winter wheat (Baethgen and Alley, 1989b; Scharf and Alley, 1993). Also of interest are critical levels, the concentration at which further N additions are unlikely to elicit a positive grain yield response. Critical TN levels for soft red winter wheat in the eastern United States are well established, ranging from 35-41 g N kg^{-1} (Weisz et al., 2007). Little published research addresses critical levels in HRW wheat, with the exception of a study in Colorado, where a critical level of 32 g N kg^{-1} was indicated (Vaughan et al., 1990). Besides the lack of information regarding HRW wheat, research has not addressed the relationship of TN and GPC. Given that both grain yield and GPC are influenced by available N, a strong relationship may well exist between TN and GPC. It may be possible to determine a critical level for GPC, which could help producers achieve production goals more consistently.

Plant biomass and GS influence the relationship of TN and yield (Engel and Zubriski, 1982; Weisz et al., 2007). In North Carolina, critical levels were highest, and model fit poorest when biomass at sampling was below 340 kg ha^{-1} (Weisz et al., 2007) In this same study, the difference in critical TN predicted from low and high biomass sample plots was 36.8 g kg^{-1}. After emerging from winter dormancy TN rapidly decreases, underscoring the importance of sample collection at identical growth stages when evaluating TN levels (Karlen and Whitney, 1980). Literature relating biomass to critical TN is generally lacking for other regions and wheat classes. Variation among published values and determining factors indicate that GS 30 plant tissue N requires calibration and multi-year evaluation before introduction as a viable N management tool (Baethgen and Alley, 1989b; Engel and Zubriski, 1982; Roth et al., 1989; Weisz et al., 2007).

Genotypic differences may also explain some variation among published critical levels. Tissue N concentration at GS 30 differed among thirty-six Australian varieties and breeding lines (Rostami and O'Brien, 1996). Maturity differences explained much of the variation, with earlier varieties generally expressing lower N concentration, lower GPC, and higher yield under the experimental growing conditions. This study did not address N critical levels specifically but strongly suggests a genotypic component to this measure. Engle and Zubriski (1982) also observed significant genotypic effects on TN but these authors suggest that accurately identifying GS at sampling is more critical to use of the TN test than accounting for varietal influences.

Flag leaf nitrogen (FLN) concentration is another indicator of plant N status. The FLN test is best suited to determine N sufficiency for GPC, as grain yield is less responsive to N by the time the flag leaf unfolds. Critical values are relatively well established for HRS wheat, in which case minimal response to N may be expected when FLN exceeds 42 g kg^{-1} (Tindall et al., 1995; Wescott et al., 1997). Published critical values regarding HRW wheat are less consistent. Brown and Petrie (2006) reported FLN associated with 120 g kg^{-1} GPC as 43.6 and 45.2 g kg^{-1} in 1985 and 1987, respectively for irrigated HRW wheat in southern Idaho. These results would seem to suggest a similar relation of FLN and GPC in both winter and spring wheat, except that a critical value of only 34.5 g kg^{-1} was observed in 1986. Actual critical levels in this study corresponded to higher GPC, and were 50 g kg^{-1} in 1985 and 1987, but 37 g kg^{-1} in 1986. In the nearby Treasure Valley of Oregon, 125 g kg^{-1} GPC was associated with FLN of 38 g kg^{-1}, but the determined critical level was placed at 44 g kg^{-1} (Shock et al., 1986). Little additional research is available concerning the FLN test in HRW wheat and is conspicuously absent for dryland systems such as those common in northeastern Oregon. Dryland producers could improve late season N management if a valid relationship between FLN and GPC were defined and acceptable methods to apply late season N were demonstrated.

Proper sampling methodology is critical for obtaining meaningful FLN test results. Sampling time will significantly impact test results. Flag leaf nitrogen generally decreases from flag leaf emergence to senescence, particularly following anthesis (Brown et al., 2005). Research used to determine FLN critical levels has generally emphasized sampling when 50% of heads are emerged from the boot (Brown et al., 2005; Tindall et al., 1995). Sampling prior to heading has the advantage of giving additional time for analysis and decision making, but may positively bias results since FLN typically declines as the plant matures.

A sampling scheme which adequately represents field scale N status is likewise important for using the FLN test. This is typically not an issue in research scale experiments but presents a formidable challenge in production fields. Small experimental plots are adequately characterized by relatively few flag leaves. Taking an equally representative sample in a commercial field, however, would require thousands of leaves. Labor and laboratory costs prohibit such extensive sampling.

Less intensive sampling may give an unreliable estimate of N status. This, as well as variation in sampling time were suggested as possible explanations for the failure of FLN to predict adequate GPC of HRS wheat grown in 48 producer fields under irrigation in central Oregon (Brown, 2001). Normalization of FLN data may help correct for some sources of variation. Brown and Petrie (2005) demonstrated the effectiveness of normalization to account for year effects in their FLN datasets. This approach may also be useful to correct for differences in sampling time. Normalizing data requires additional samples from an extra fertilized N rich strip or region, which some producers may find cumbersome.

Conclusions

Decades of research have contributed to our understanding of N for wheat production in both the PNW and beyond. Most studies in northeastern Oregon have focused on SWW wheat, the region’s primary production class. Market premiums available for HRW have sparked renewed interest in this wheat class which calls for a reevaluation of management practices for high GPC wheat production.

Available N influences multiple aspects of wheat growth and development. Adequate available N at critical growth stages is a prerequisite for achieving high grain yield and GPC. However, high levels of soil and fertilizer N do not necessarily equate to availability. Soil moisture, precipitation patterns and location of N within the soil profile strongly influence N availability and plant utilization thereof. High temperatures and moisture stress can also influence physiological processes key to grain yield and protein formation. These factors are highly unpredictable. Therefore, managing for these may entail relegating HRW production to higher stress regions where high yield is less likely to dilute GPC to undesirable levels. Regardless of environment, selection of a variety expressing good yield and high GPC is also necessary. Breeders have successfully developed superior varieties in other regions, but detailed fertility trials are needed to positively identify which locally adapted varieties perform best in northeastern Oregon.

Current fertilizer N recommendations and practices emphasize fertilizer N application in the fall, and incorporate relatively little data from HRW production. Other wheat producing regions have used split and late N applications to improve grain yield and GPC, practices which deserve more attention in northeastern Oregon. Plant TN at GS 30 and FLN have been used to indicate when such practices would be effective. Only minimal research has addressed these practices in northeastern Oregon; therefore the potential remains for their development as N management tools.

Thesis Objectives

- Characterize the relationship between fertilizer N, grain yield and GPC of HRW wheat in the dryland growing regions of northeastern Oregon
- Compare the yield and GPC performance of three commercially available HRW wheat varieties
- Evaluate the accuracy of current N recommendations for HRW production
- Determine the effect of spring N application on grain yield and GPC
- Investigate the potential for GS 30 TN to predict grain yield and GPC
- Assess the ability of FLN to predict GPC
- Characterize the suitability for HRW production of study environments and identify possible strategies for improving N management

NITROGEN MANAGEMENT AND VARIETY SELECTION FOR DRYLAND PRODUCTION OF HARD RED WINTER WHEAT IN NORTHEASTERN OREGON: EFFECT OF NITROGEN FERTILIZER RATE, VARIETY, AND LOCATION

Abstract

Proper nitrogen (N) management and variety selection are important for profitable hard red winter (HRW) wheat production in the dryland growing regions of northeastern Oregon. However, N management for grain yield and grain protein concentration (GPC) is challenging in these dryland systems due to climate differences between locations and seasonal weather influences. Current fertilizer guides make only small distinctions between locations in terms of N management and incorporate relatively little data from HRW production. Identifying adequate N management practices and scenarios suitable for HRW production will help producers reduce risk and enhance profits. This study investigates the effects of fertilizer N rate, variety, year, and location over six site-years in northeastern Oregon from 2007 to 2009. A site at Pendleton, Oregon represented an intermediate precipitation zone (420 mm), while sites as Lexington and Arlington, Oregon were in a low precipitation (250-300 mm) zone. Yield response to fertilizer N was generally small, and even negative when high soil N and drought stress coincided. Grain protein concentration response to fertilizer N was significant, and varied by year and location. Some site-years proved favorable for efficient production of high GPC HRW wheat, whereas acceptable GPC was very difficult to achieve in others, underscoring the difficulty of managing N for both yield and GPC in these environments. Study varieties differed in yield potential and GPC, and these patterns were consistent across site-years. Varieties ‘Norwest 553’ and ‘Boundary’ exhibited highest yield, while ‘Norwest 553’ and ‘Agripro Paladin’ expressed the greatest GPC. Major differences between soil N use efficiency (NUE_s) and fertilizer use efficiency (NUE_f) were observed at all sites, but NUE_f was substantially less at low precipitation sites, often falling well below 20% where moisture conditions were poor. Current N recommendations did not accurately describe N response observed in this study, often underestimating N requirements, particularly in the low precipitation environments. Adjustments for differences in NUE_s and NUE_f among locations may improve guidelines. Study results also suggest that HRW production is most suited to situations of high soil N and at least average yield potential.

Introduction

Soft white winter wheat (SWW) is the primary wheat market class produced in Oregon (NASS, 2004-2009). Production of a nontraditional market class such as hard red winter (HRW) wheat has the potential to increase grower profits. For grain delivered to Portland, Oregon, higher market value of HRW wheat is generally associated with grain protein concentration (GPC) of 115-125 g kg^{-1} or more. From 1998 to 2009, market value per Mg of 120 g kg^{-1} GPC HRW wheat at Portland has averaged $19 more than SWW wheat. At times this premium has exceeded $55 per Mg, and at others has fallen to less than bids for SWW wheat (USDA unpublished, 2010).

Proper nitrogen (N) management is essential to produce HRW wheat that meets both grain yield and GPC expectations. Grain protein concentration of 125 g kg^{-1} is the standard for millers and bakers (PNW WQC, 2007). Achieving this “target” GPC requires that wheat take up N in excess of yield requirements, which can be achieved with addition of fertilizer N to crops (OSU, 1970).

Determining the quantity of N necessary to achieve optimum yield and target GPC is complex. Numerous interactions between the soil, moisture, residual N, weather patterns, management practices, and the crop itself may change or modify the main effects of N (Cochran et al., 1978; Olson et al., 1976; Rao et al., 1993; Vaughan, 1990) The PNW is characterized by a Mediterranean climate, with cool moist winters followed by hot, dry summers. The wheat growing regions of northeastern Oregon may be further classified into many distinct micro-climates, within which there is considerable year to year weather variation. As a consequence of this variation achieving target GPC consistently has been difficult in northeastern Oregon.

Oregon State University fertilizer guides use a yield based approach. Nitrogen needs are expressed as the ratio of N required per unit grain production at a desired GPC (table 2.1). Fertilizer N needs are equal to the product of this ratio and anticipated grain yield minus soil inorganic N in the top 120 cm and expected in-season mineralization. Alternatively, the N requirement for high GPC HRW production is given as 7 kg N Mg^{-1}

above rates necessary to achieve maximum yield for SWW wheat (Brown et al., 2005; Flowers et al., 2007).

Table 2.1 Current Oregon State University nitrogen recommendations per unit grain production (kg Mg^{-1}) at corresponding grain protein concentration goals (g kg^{-1})

Protein Goal	Nitrogen Requirement	Average
90	33 - 40	37
100	37 - 43	40
110	40 - 48	45
120	43 - 53	50
130	47 - 58	55

Source: Lutcher et al. (2007)

These recommendations may not be adequate for HRW production. Nitrogen recommendations for higher GPC (>110 g kg^{-1}) in Oregon were derived primarily from N uptake studies with HRS wheat. Given the longer growing season and higher yield potential of HRW wheat, one may reasonably assume that N requirements for HRW wheat production could deviate from these recommendations. Furthermore, GPC at optimum yield is not well defined for HRW wheat in northeastern Oregon. Reports from irrigated wheat in southern Idaho, and dryland production in the Great Plains place this value at 120 and 115 g kg^{-1}, respectively (Brown and Petrie, 2006; Smika and Greb, 1973). Grain protein concentration of 130 g kg^{-1} indicated sufficiency in Saskatchewan, Canada (Fowler et al., 1990). This contrasts with SWW wheat traditionally grown in northeastern Oregon, for which optimum yield corresponds to 83-100 g kg^{-1} GPC (Glenn et al., 1985; Lutcher et al., 2007)

The level of N that actually satisfies requirements for both yield and GPC depends upon efficient use of both soil and fertilizer N resources. Raun and Johnson (1999) defined nitrogen use efficiency (NUE) as:

NUE = [(total cereal N removed) – (N coming from the soil + N deposited in the rainfall)/ (fertilizer N applied to cereals)]

This approach is useful for HRW wheat production as it emphasizes grain N accumulation. However, this method fails to specify which variables most influence NUE, such as fertilizer versus soil N uptake efficiency, N partitioning within the wheat plant (Huggins and Pan, 1993) and application method (Schlegel et al. 2003).

Nitrogen use efficiency and available N are often negatively correlated. When N supply is inadequate for optimum yield, as much as 80% of N may be recovered in the grain alone. As available N increases uptake capacity eventually becomes saturated, at which point percent recovery of additional N equals zero (Fowler et al., 1990). Thus, higher N rates for achieving GPC may hold negative implications for NUE. Leaving large amounts of N in the soil can also have adverse environmental consequences (Brady and Weil, 1999; Halvorson et al., 1972). Leaching is minimal in semi-arid northeastern Oregon, but given time over-application of N could still adversely impact groundwater resources.

Although NUE is generally greatest where moisture is sufficient to sustain greater yield (Kolberg et al., 1996; Meisinger et al., 2008) GPC tends to be lower in such environments due to the diluting effect of starch on GPC. This negative relationship between grain yield and GPC is noted by multiple researchers (Costa and Kronstad, 1994; Cox et al., 1985; Terman et al., 1969). For this reason, it is believed that HRW wheat in Oregon is best suited to high stress, low yield environments (Thompson, 1972). However, research on irrigated HRW and HRS wheat shows that with proper N management both yield and GPC targets can be obtained in low stress, high yielding environments (Brown and Petrie, 2006; Shock et al., 1986).

Variety selection is also important for profitable HRW production. Historically, HRW varieties yield less than their SWW counterparts (Brown et al., 2005; Shock et al., 1986). Lower yield varieties may express higher GPC, but this trade off may not be necessary. For example, both high yield and GPC have already been documented for varieties used in the Great Plains (Cox et al., 1985; Johnson et al., 1973). Anecdotal evidence from the

Oregon State University statewide variety trials suggests that some new HRW wheat varieties may also possess this character (Flowers et al., 2009) but further study is warranted to confirm these observations.

Research has greatly improved our understanding of how N interacts with other factors to influence grain yield and GPC of wheat. Nevertheless, many questions remain concerning N management for yield and GPC in northeastern Oregon. The following research seeks to understand the relationship of N to both grain yield and GPC across two contrasting precipitation environments over several growing seasons. Soil N use efficiency (NUE_s) and fertilizer N use efficiency (NUE_f) are calculated to determine relative contribution of these two pools for production purposes, and three HRW varieties are evaluated for grain yield and GPC performance. Understanding these issues will serve to evaluate the adequacy of current N guidelines, assist in identifying high performing varieties, and specify which locations may be most suitable for HRW wheat production.

Materials and Methods

Field trials were established at three locations in northeastern Oregon in 2007 to 2009. Trials were located at Pendleton in 2008 and 2009, Lexington in 2007 to 2009, and Arlington in 2009. The study site at Pendleton was located at the Columbia Basin Agricultural Research Center. Lexington and Arlington sites were located on grower-cooperator farms.

The wheat growing region of northeastern Oregon has been previously divided into ‘intermediate’ and ‘low’ precipitation zones (Douglas et al., 1990). The Pendleton site was located in the intermediate precipitation zone (420 mm). Lexington and Arlington represented the ‘low precipitation’ (250-300 mm) zone. Each site-year was fallow the previous season. Pendleton and Arlington sites were managed with conventional tillage. A no-till chemical-fallow system was used at Lexington. Sites were repositioned to different fields within locations each year to avoid plot residual effects and maintain the fallow-crop sequence.

Soil residual N in the top 90 cm was measured shortly after planting from soil cores collected in 30 cm increments. Cores were extracted from two unfertilized check plots within each block for a total of eight cores. Soil from each depth increment was pooled, homogenized, and taken for lab analysis. Nitrogen concentration was reported as NO_3-N and NH_4-N in parts per million which were converted to area units using a conversion factor of 4.1 kg N ha^{-1} ppm^{-1}.

Growing conditions varied considerably by year and location. Soil N levels of check plots at planting, and monthly precipitation for fallow and growing years are summarized in tables 2.2 and 2.3, respectively. Planting at Pendleton was performed on October 15, 2007 and October 8, 2008. Dates for Lexington were September 27, 2006, September 26, 2007 and September, 23, 2008. Arlington was planted on September 22, 2008.

Treatments were a factorial arrangement of four wheat varieties and seven fertilizer fall-applied N rates. Individual treatments were planted in 1.5 x 6 m plots arranged in a randomized complete block design with four replications. Seeding rate was 97 kg seed ha^{-1} at all sites, but row spacing was 30 cm at Pendleton, versus 38 cm for remaining sites. Nitrogen treatments were adjusted according to the yield potential of each precipitaion zone. Fertilizer N rates at Pendleton ranged from 0 to 337 kg N ha^{-1} in 56 kg increments. Corresponding rates at Lexington and Arlington were from 0 to 168 kg N ha^{-1} in 28 kg increments. A drill capable of banding fertilizer was unavailable; therefore the seeding drill was used to place fertilizer between and slightly below the seeding row immediately prior to planting. At Pendleton, fertilizer N was applied in similar fashion approximately one month prior to planting. Nitrogen source for all applications was granular urea (46-0-0). Potassium magnesium sulfate (K-Mag$^{®}$, 0-0-21.5-21) was also applied to all plots, regardless of location, at the rate of 13.5 kg S ha^{-1} to eliminate any potential sulfur deficiencies.

The following four varieties were evaluated: ‘Norwest 553’, ‘Agripro Paladin’, ‘Boundary’, and ‘Stephens’. Norwest 553 and Agripro Paladin are more recent HRW releases from Oregon State University and Agripro, respectively. Boundary, a 1998 HRW release from the University of Idaho, was chosen as a standard HRW standard from which to compare the two more recent HRW releases. Soft white winter variety Stephens has been grown in the region for over 30 years, and was included as a long term check.

Plots were harvested at physiological maturity with a Hege small plot combine (Wintersteiger Inc., Salt Lake City, Utah, USA). Grain moisture and test weight were recorded, and reported grain yield was adjusted to 12% moisture. Grain protein concentration was estimated using NIR transmittance spectroscopy with an Infratec™ 1241 Grain Analyzer (Foss Analytical, Slangerupgade, Denmark).

Table 2.2 Soil residual nitrogen (kg N ha^{-1}) at planting in the top 90 cm of soil at Pendleton, Lexington, and Arlington

Pendleton Nitrogen Form	2007	2008	2009
NO_3-N	-	105.9	97.6
NH_4-N	-	12.0	20.1
Total	-	117.9	117.7
Lexington			
NO_3-N	102.9	42.3	82.7
NH_4-N	4.4	7.3	8.8
Total	107.3	49.6	91.5
Arlington			
NO_3-N	-	-	53.0
NH_4-N	-	-	22.6
Total	-	-	75.6

Table 2.3 Fallow and crop year precipitation in millimeters by month at Pendleton, Lexington, and Arlington

Month	**Pendleton**			**Lexington**				**Arlington**	
	2007	2008	2009	2006	2007	2008	2009	2008	2009
August	0	9	15	0	0	4	8	7	5
September	19	7	3	4	9	12	0	0	0
October	21	33	5	20	32	24	10	27	7
November	90	53	39	30	42	39	3	34	13
December	59	60	71	77	47	30	25	17	40
January	16	45	52	54	16	25	25	44	35
February	45	16	36	18	31	11	22	5	27
March	42	56	65	34	19	15	39	21	20
April	28	13	45	27	25	7	17	4	9
May	24	33	36	51	20	29	26	18	24
June	29	34	29	42	27	20	20[†]	10	6
July	8	3	0	6	3	0	0	0	-
Total	380	362	396	362	272	217	195	187	185

[†] Weather station located two kilometers from study site. Amount does not include estimated 8-13mm deposited by a localized thunderstorm on June 12, 2009.

Straw biomass N concentration was also determined for all sites in 2008 and 2009. Plots were harvested as near the ground as possible with the plot combine and straw was then collected and weighed in tared plastic containers on a tripod equipped with a 0.05 kg accuracy scale. Random samples of straw (>40 g) were also collected from each plot, weighed, dried in a forced air dryer for 48 hours, ground to pass a 0.7 mm screen, and analyzed for total N concentration using the Kjeldahl method (Foulk et al., 1952).

Statistical analyses were performed using SAS statistical software (SAS, 2003). Analysis of variance was performed with the PROC GLM procedure. Linear and quadratic regression showing the relationship between N rate and GPC at each site year was performed using the PROC REG procedure. Least significant difference (LSD) mean separation was performed using the MEANS statement with default significance set at $p \leq 0.05$. Variety performance was evaluated by using t-tests to compare means of combined data from all fertilizer N treatments for each HRW variety.

All varieties were included for analyses of yield, test weight, and straw biomass. For the response variables GPC, N harvest index (NHI), NUE_s and NUE_f, a subset of data containing only HRW varieties was used for statistical analysis. Fertilizer use efficiency in this study was computed as:

$$NUE = (grain\ N + straw\ N) / (soil\ N + fertilizer\ N).$$

Soil NUE corresponds to the mean N recovery of plots not receiving fertilizer N. Experimental values for N requirements (kg N Mg^{-1} grain) at various GPC goals were obtained from regression equations relating the N requirement ratio to GPC within the range of actual observations.

Results and Discussion

Grain yield: intermediate precipitation

Fertilizer N significantly improved yield at Pendleton in both 2008 and 2009 (figure 2.1, appendix 4.1). The range of response was fairly narrow, however, since yield was generally optimized with only 56 or 112 kg N ha^{-1} of fertilizer. Yields of adequately fertilized plots were similar to that reported by producers in this region. Maximum combined yield of all varieties were statistically different between years, totaling 6.4 and 6.7 Mg ha^{-1} in 2008 and 2009, respectively. Yield tended to decline at fertilizer rates greater than 224 kg N ha^{-1}, but these differences were not always significant.

Yield: low precipitation

Fertilizer N significantly influenced yield at three of the four site-years at Lexington and Arlington (appendix 4.2). Yield was improved by fertilizer N at Lexington in 2008. Fertilizer N additions reduced yield at Lexington in 2007, and both Lexington and Arlington in 2009 (figure 2.2). Maximum mean yield at Lexington was 3.3 Mg ha^{-1} in 2007, which is comparable to the long term average for this location. Below normal precipitation in 2008 and 2009 (table 2.3) resulted in lower maximum mean yield of only 2.5 Mg ha^{-1} in these years at Lexington. Below normal precipitation resulted in a mean yield of 2.0 Mg ha^{-1} at Arlington in 2009. Yield reduction with higher N rates at Lexington ranged from 4-20% in 2007 and 3-17% in 2009. Losses were somewhat less dramatic at Arlington in 2009, and ranged from 4-10%. Large negative response to N treatments at Lexington was not a surprise considering the high level of soil N present in 2007 and 2009. While fertilizer N increased yield at Lexington in 2008, the difference was only significant for the first 28 kg N ha^{-1} increment for Norwest 553 and Boundary, and yield trended downward at rates above 84 kg N ha^{-1}. High N levels promote excessive vegetative growth, which can rapidly draw down soil moisture levels and exacerbate conditions of late season drought (McDonald, 1989; van Herwaarden et al., 1998a). Rainfall patterns in the PNW are such that wheat crops in these drier regions nearly always experience terminal drought to some degree, which increases their vulnerability to the consequences of over fertilization, as observed in this study. Clearly, when soil N levels are high, considerable care must be taken to avoid over fertilization at these and similar low precipitation locations if maximum yields are to be achieved.

Grain protein concentration: intermediate precipitation site

Grain protein concentration was positively correlated with fertilizer N rate at Pendleton. Fertilizer treatments created a wide range of GPC ranging from near 80 g kg^{-1} to over 140 g kg^{-1} in some treatments. Grain protein concentration response to N differed by year, as indicated by a highly significant year x N rate interaction (appendix 4.3). The

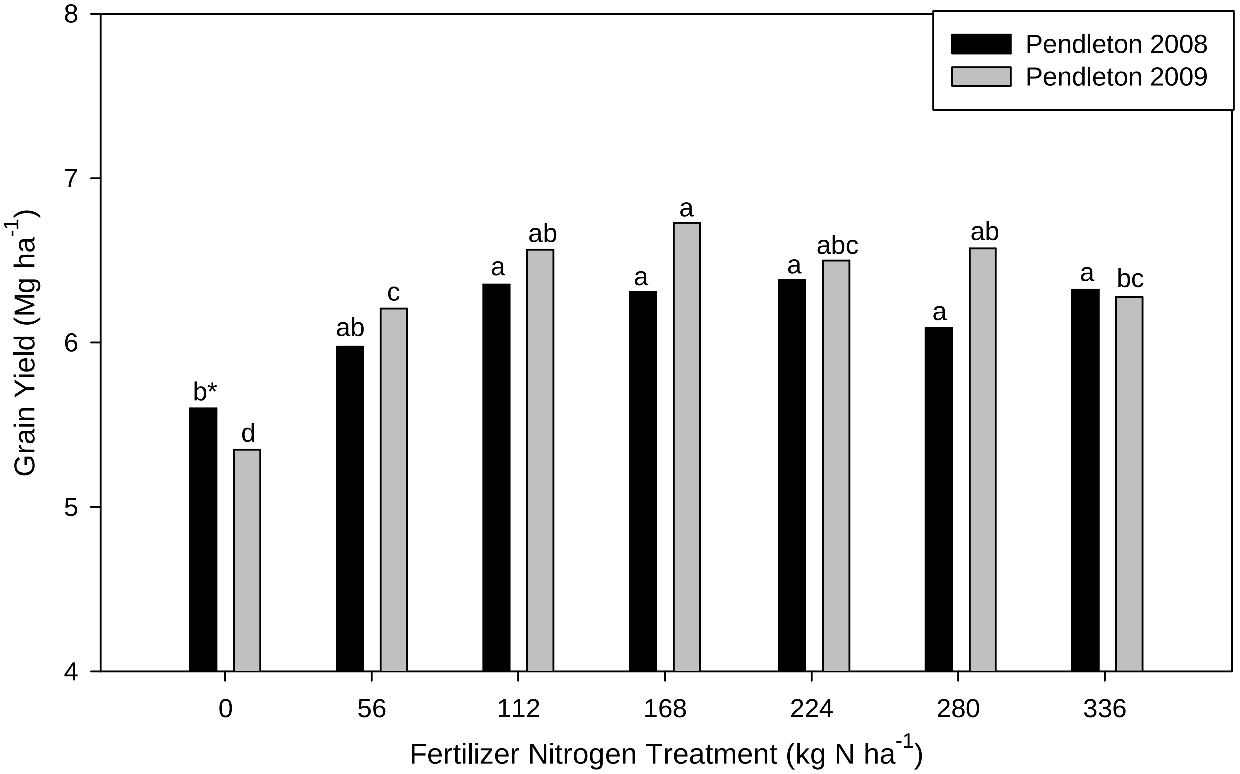

Figure 2.1 Combined mean yield of all varieties at increasing fall applied nitrogen fertilizer rates at Pendleton in 2008 and 2009

* Yield followed by same letter not significantly different ($p \leq 0.05$) within each year

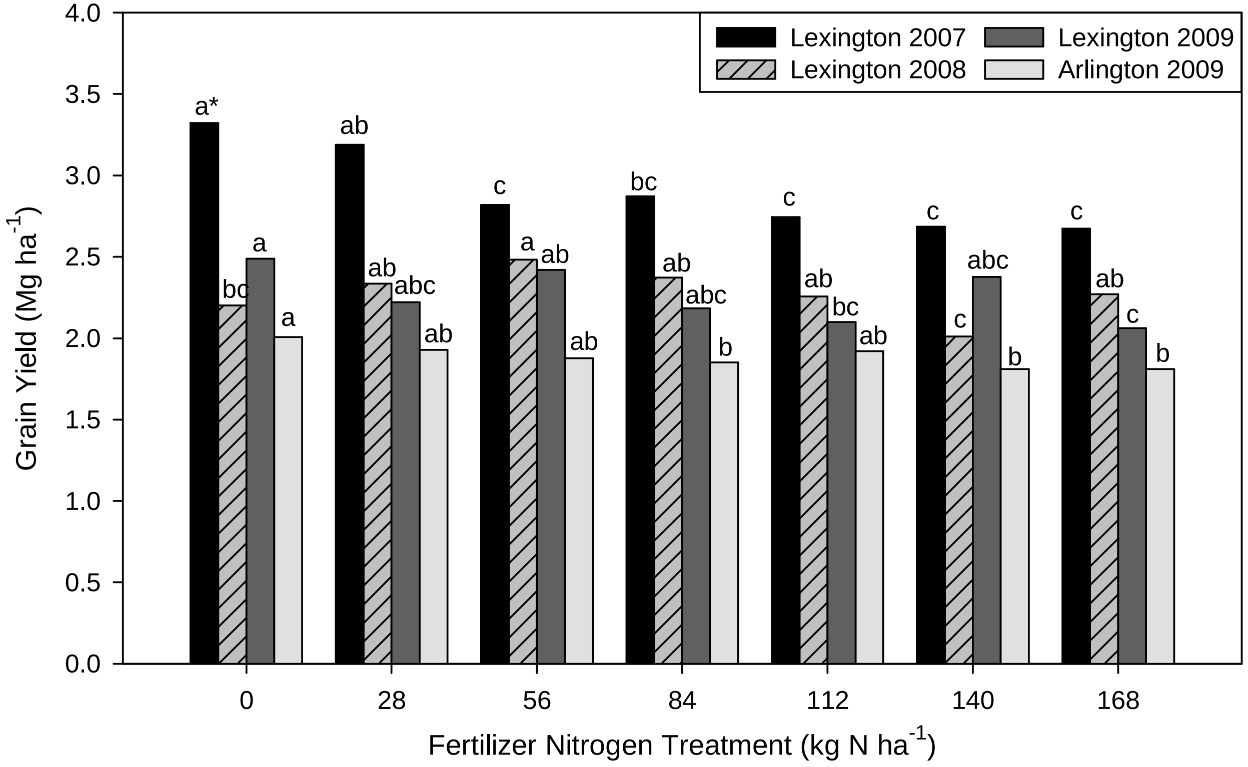

Figure 2.2 Combined mean yield of all varieties at increasing fall applied nitrogen fertilizer rates at Lexington and Arlington from 2007 to 2009

* Yield followed by same letter not significantly different ($p \leq 0.05$) within each year

N rate x variety interaction was not significant, indicating that the general relationship did not differ among varieties. Therefore, means of HRW varieties were combined for regression analysis. Simple linear and quadratic models were adequate to characterize GPC response to N rate (figure 2.3).

Models explained 79% and 65% of variation in 2008 and 2009, respectively. Grain protein concentration was most responsive to N treatments in 2008. Up to the 224 kg N ha^{-1} rate, GPC in 2008 increased approximately 9.1 g kg^{-1} for every 56 kg N ha^{-1} increment of fertilizer N, but began to plateau at fertilizer rates of 224-281 kg N ha^{-1}. The 2009 coefficient was less than half of that in 2008, with each increment on N increasing GPC only 4.3 g kg^{-1}. Greater N response in 2008 resulted in reaching or exceeding target GPC of 125 g kg^{-1} at N treatments between 168 and 224 kg N ha^{-1}. In 2009, target GPC required fertilizer rates of 280 kg N ha^{-1} or more.

The disparity in response to N between years is notable given the minimal differences in grain yield, and illustrates the difficulty of estimating N needs for GPC in this region. Late season rainfall is cited both by researchers (Horneck and Lutcher, 2001; Smika and Greb, 1973) and growers alike for failure to meet target GPC at customary N rates. However, substantial rainfall or cool temperatures during grain fill did not appear to be significant factors. Rather, small changes in rainfall distribution, soil N and moisture dynamics, and temperature between seasons likely contributed to these differences. Although not considered at the onset of this study, straw biomass may have also influenced GPC. Depending upon treatment, mean straw biomass in 2009 was 11-39% less than in 2008, despite comparable yield (appendix 4.4). Reduced quantities of straw biomass relative to grain yield (i.e. greater harvest index) limit the quantity of N in vegetative biomass available for translocation to the grain (Kramer, 1979). Lower straw biomass in 2009 resulted from late stand establishment, which compressed the growing season. Mean plant height of HRW varieties was 9.6 cm shorter in 2009(data not shown). Tillering may have been affected, but stems were not counted to confirm this.

Grain protein concentration: low precipitation sites

Applying fertilizer N also significantly increased GPC at Lexington and Arlington, creating a large range of values. Again, analysis of variance indicated a significant effect for year

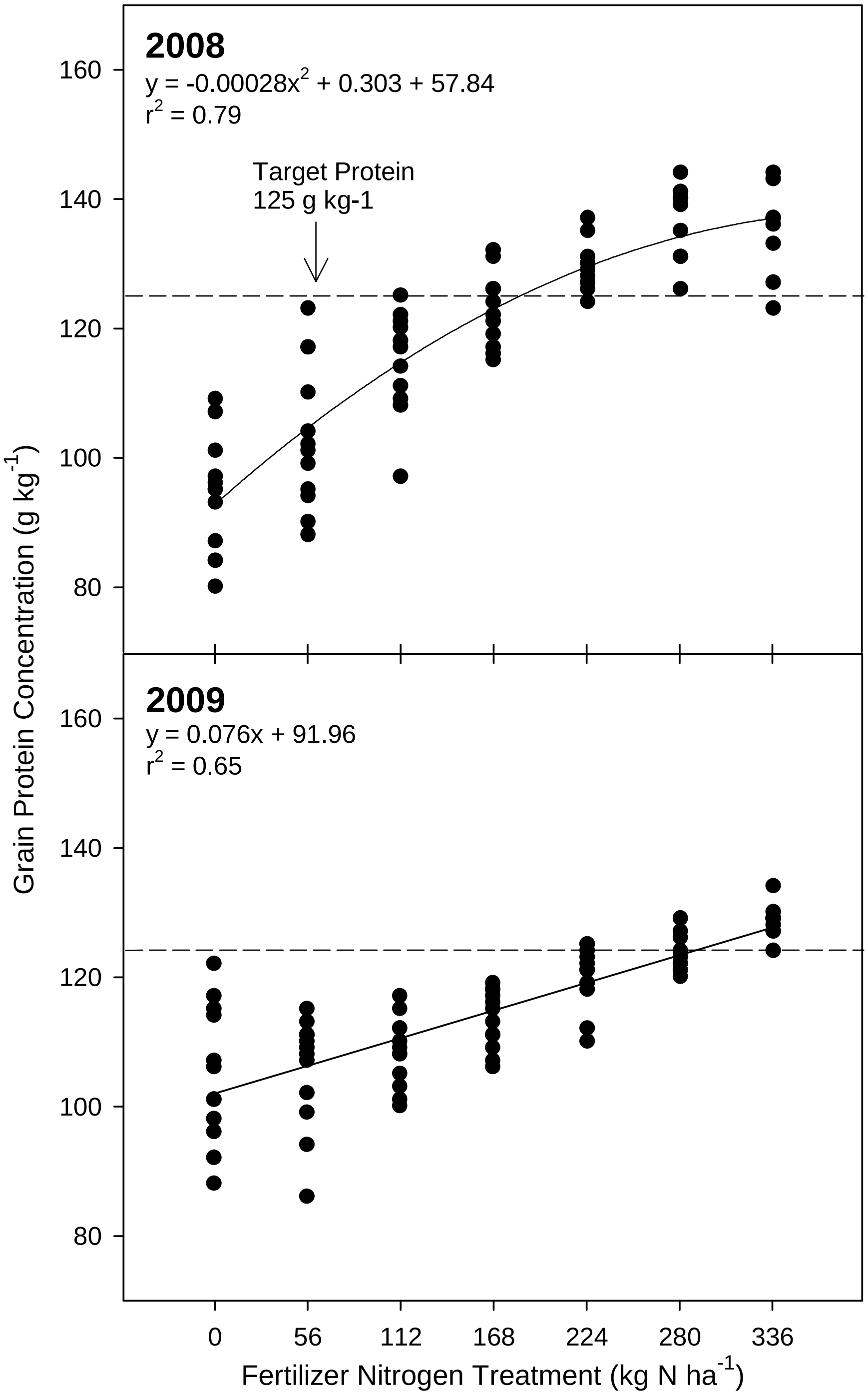

Figure 2.3 The relationship of fall applied fertilizer nitrogen rate to grain protein concentration at Pendleton in 2008 and 2009

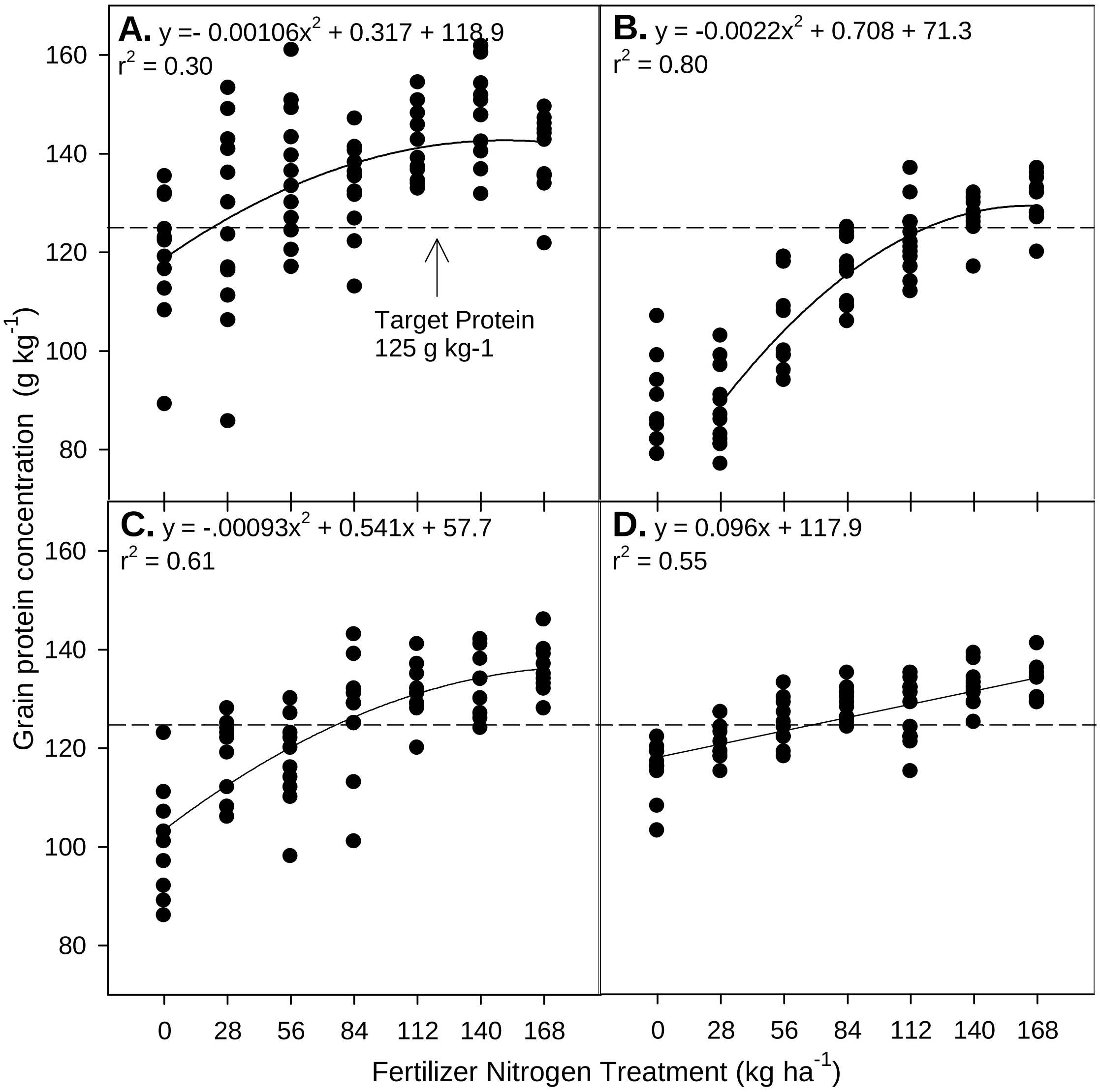

Figure 2.4 The relationship of fall applied fertilizer nitrogen rate to grain protein concentration at Lexington 2007 (A), Lexington 2008 (B), Lexington 2009 (C) and Arlington 2009 (D)

but not for variety and its interactions (appendix 4.5). Response to N was characterized by both linear and quadratic models (figure 2.4) Quadratic terms were significant for most models. Response to N was greatest at Lexington in 2008. In this case, the zero fertilizer N rate was excluded from regression analysis since increased yield caused by the first 28 kg N ha^{-1} increment of fertilizer N diluted GPC. As a result, a positive GPC response to N was not observed until the 56 kg N ha^{-1} rate. Thereafter, GPC increased roughly 51 g kg^{-1} for each 28 kg N ha^{-1} increment until leveling off around the 112 kg N ha^{-1} rate. Arlington was the least N responsive site, in which GPC increased only 26 g kg^{-1} for each increment of fertilizer N.

Soil N levels likely played a significant role in the different responses among site-years. Very high residual soil N at Lexington in 2007 nearly eliminated any need for fertilizer N to achieve target GPC. In fact, GPC enhancement with fertilizer N coincided with yield loss at Lexington in both 2007 and 2009, indicating that yield reduction drove GPC increase rather than greater assimilation and partitioning of N to the grain. In contrast, soil N was very low in 2008 (table 2.2). This resulted in greater GPC response to the first increments of fertilizer N. Higher soil N at both Arlington and Lexington (table 2.2) in 2009 explains the lack of yield response to N treatments, but does not explain why fertilizer N did not enhance GPC more that it did. Late stand establishment due to a very dry fall may have contributed to this result at these sites in 2009. As of November 28, 2008 emergence at Lexington was only 50%, and not more than 10% at Arlington. Lower N uptake before dormancy may not have been compensated by N uptake in the spring.

Nitrogen use efficiency: intermediate and low precipitation sites

Differences in both NUE_s and NUE_f were observed between Pendleton and remaining sites. However, data followed similar trends regardless of location, indicative that factors influencing NUE were generally analogous across sites. Soil nitrogen use efficiency was generally high. Mean NUE_s among unfertilized check plots at Pendleton totaled 77% and 80% in 2008 and 2009, respectively (figure 2.5).

Soil NUE was 69% at Lexington in 2008 when only 49.6 kg N ha^{-1} was present in the soil (table 2.2). A Lower NUE_s value of 53% was observed at both Lexington and Arlington in 2009. Compared to Pendleton, reduced NUE_s was expected at Lexington and Arlington since soil moisture is positively correlated with NUE in general (Kolberg et al., 1996; Meisinger et al., 2008). A combination of low residual soil N and greater precipitation during the fallow year prior to 2008 were favorable for the higher observed NUE_s at Lexington that season. In contrast, high soil N relative to yield potential (a function of soil moisture) resulted in lower NUE_s in 2009.

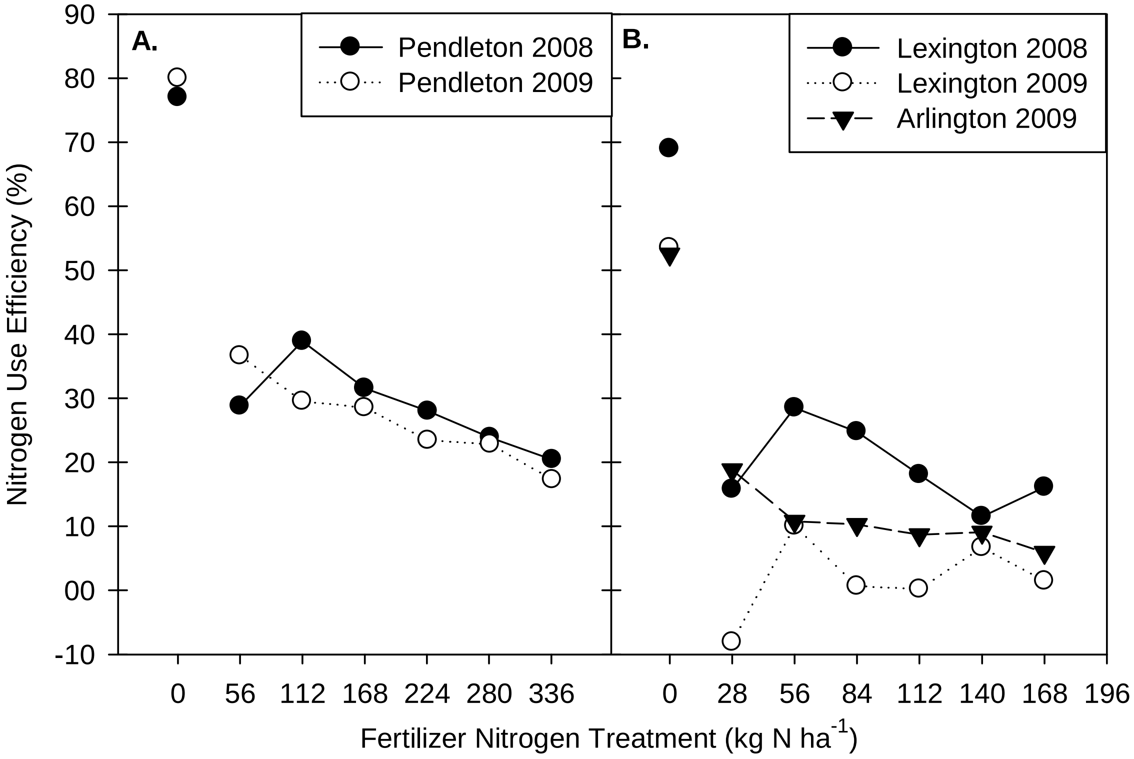

Figure 2.5 Soil nitrogen use efficiency (zero rate) and the relationship of fall applied nitrogen fertilizer rate to fertilizer use efficiency among site-years at Pendleton (A), and both Lexington and Arlington (B)

Fertilizer use efficiency declined with increasing N rate at all site years, which is consistent with observations from previous research (Fowler et al., 1990; Knowles et al., 1994; Smika and Grabouski, 1976). At Pendleton, mean NUE_f values for the 56-112 kg N ha^{-1} treatments, which generally corresponded to requirements for yield, fell between 29% and 39% in both years. Although NUE_f for yield was similar both years, target GPC of 125 g kg^{-1} was achieved at NUE_f values of 27-32% in 2008 and 17-23% in 2009.

At Lexington and Arlington, NUE_f at optimum yield could not be determined since a positive yield response was not generally observed at these sites. Target GPC of 125 g kg^{-1} was achieved in 2008 between the 112 and 140 kg N ha^{-1} rates, which corresponded to NUE_f values of 18% and 12%, respectively. Higher soil N at both Lexington and Arlington in 2009 resulted in achieving target GPC with less fertilizer (56-

84 kg N ha^{-1}), but corresponding NUE$_f$ values were only 1% and 11% at the two locations, respectively. Extremely low and even negative NUE$_f$ values at Lexington in 2009 indicate that yield reduction, rather than greater total assimilation of fertilizer N, drove GPC increase that year. At Arlington, values for NUE$_f$ never reached zero, showing that net N uptake was at least increased slightly with fertilizer treatments at this site. Considering all site-years from Lexington and Arlington, it is clear that applying large amounts of fertilizer N was not a good strategy for improving GPC in the years of this study. Particularly in 2009 at these low precipitation sites, GPC enhancement with fertilizer N was at best extremely inefficient, and at worst only achieved by reducing yield. In the latter case, addition of fertilizer N ran contrary to the goal of optimizing both yield and GPC simultaneously.

Compared to other regions, high NUE$_s$ values in check plots is consistent with observations from previous studies (Fowler et al., 1990; Sowers, 1994). Actual NUE$_f$ values vary considerably within the literature. Sowers et al. (1994) observed NUE$_f$ values equal to and even greater than those for NUE$_s$, which averaged between 60% and 74% in check plots for SWW wheat in the Palouse region of eastern Washington. Rather than GPC, some researchers have reported NUE$_f$ at maximum protein yield. In the north Texas Blackland, Knowles et al. (1994) observed a NUE$_f$ value of 41% at rates for optimum yield, and values of 32 - 33% at applications associated with maximum protein yield. Lower values similar to those at Lexington and Arlington have also been observed in Saskatchewan, Canada, where NUE$_f$ values approached zero at maximum grain yield, and reached zero at maximum grain protein yield (Fowler et al., 1990).

The large disparity between recovery of fertilizer and soil N resources in the present study suggests that the position of these two pools within the soil profile largely dictated NUE$_s$ and NUE$_f$. Although N concentrations were greatest in the top 30 cm at all sites, significant quantities were also located below 30 cm (data not shown). More uniform distribution of N with soil water therefore improved uptake (Cochran et al., 1978; Smika and Greb, 1973; Wuest and Cassman, 1992b). Deeper N is particularly important for supporting high GPC. Studies near North Platte, Nebraska demonstrated that plots with high N levels in the 60-120 cm depth (90 kg N ha^{-1}) produced the highest yield and GPC

(145 g kg^{-1}). Cochran et al. (1978) observed a similar scenario, in which GPC was increased 36 g kg^{-1} when rain and irrigation moved most N to at least 90 cm.

Post harvest soil N tests were not performed, but low NUE$_f$ values suggest most fertilizer N remained in the upper profile throughout the growing season. Without movement of N to lower depths, water depletion near the surface can leave N stranded in dry soil (Fowler and Brydon, 1989; Sowers, 1994). This was likely the scenario at Lexington and Arlington given the minimal precipitation available to percolate N into deeper layers at these sites. Greater precipitation alone at Pendleton was probably sufficient to move some N deeper in the profile, which resulted in higher NUE$_f$ values compared to other sites.

Simply applying N during the fallow season rather than banding N near the seed may have reduced stranding in the upper soil profile. Studies with HRW in Kansas showed a strong, positive relationship between GPC and the time between application of anhydrous ammonia and planting (Smika and Grabouski, 1976). Summer rainfall patterns in Kansas and the Great Plains result in greater incorporation of N applied during the fallow season. Most years in the PNW, relatively little rainfall follows spring fertilizer N application in conventional fallow. Nevertheless, fertilizing in the spring prior to fall seeding may still improve dispersion of N throughout the profile in our study region and deserves further attention. If earlier application is advantageous this would put producers using no-till management at a relative disadvantage since N is applied almost exclusively at seeding in these systems to reduce soil and residue disturbance. However, no-till producers willing to tolerate some soil disturbance could apply N into summer fallow with an undercutter.

Variety performance: grain yield

Analysis of variance indicated a significant variety main effect for nearly all site-years (appendices 4.1 and 4.2). Mean variety yield comparisons revealed that these differences were consistent across site-years. Mean yield and comparisons for each site year are summarized in figure 2.6. Norwest 553 and Boundary demonstrated high yield potential at both Pendleton and Lexington. Yield of these varieties was never statistically different from each other at any site-year, except for Lexington and Arlington

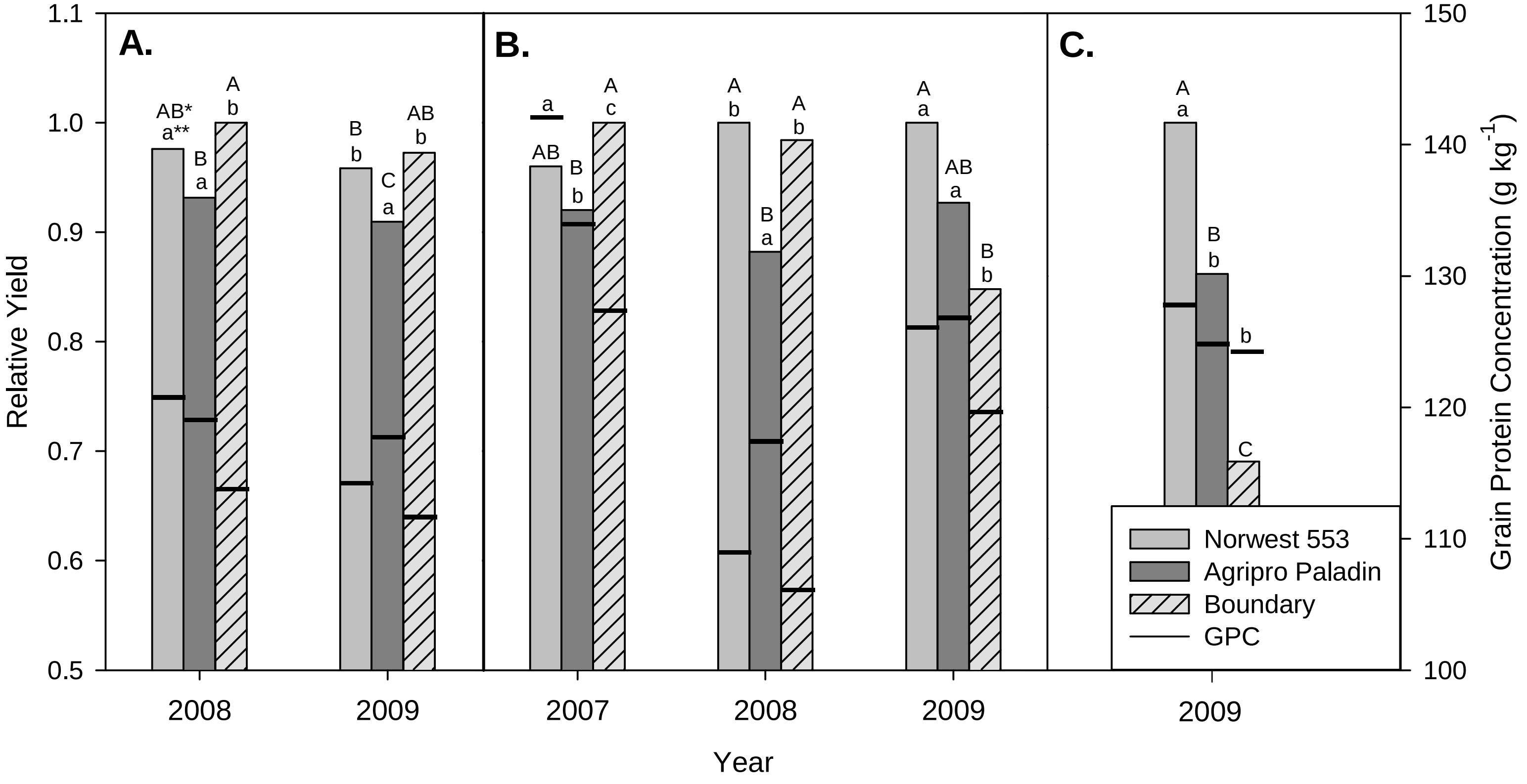

Figure 2.6 Mean relative yield and absolute grain protein concentration (GPC) of hard red winter varieties at each site-year for Pendleton (A) Lexington (B) and Arlington (C)

* Yield followed by same upper case letter not significantly different ($p \le 0.05$)

** Protein followed same lower case letter not significantly different ($p \le 0.05$)

in 2009. At these sites-years, yield of Boundary was severely curtailed by high incidence of dryland crown rot (*Fusarium pseudograminearum)*. Stephens and Norwest 553 had the lowest incidence of blank-heads, the signature symptom of dryland crown rot, and Agripro Paladin showed intermediate susceptibility (data not shown).

Excluding the 2009 data at Lexington and Arlington because of disease pressure, grain yield of Agripro Paladin was consistently lower than either Norwest 553 or Boundary. T-tests always showed Agripro Paladin as having statistically lower yield than Boundary. Compared to Norwest 553, yield of Agripro Paladin was significantly lower at Lexington in 2008 and trended lower in these same years at Pendleton. Comparison of variety rank for maximum yield supported these observations. Top mean yield each year belonged to either Norwest 553 or Boundary, and even within individual N treatments one of these two varieties nearly always occupied the top rank (data not shown).

An additional comparison of interest is that of HRW varieties to the SWW check, Stephens. Traditionally, HRW varieties have underperformed their SWW counterparts (Brown et al., 2005; Shock et al., 1986). However, compared to Stephens, little to no yield reduction was associated with the HRW varieties in this study. Norwest 553 and Boundary demonstrated yields at least as good as, if not better than, Stephens. Direct comparisons of means were not always feasible, however, since Stephens tended to reach maximum yield at lower N levels, and lost yield more rapidly at high N rates. Relative performance of Agripro Paladin depended on location. At Pendleton, yield of Agripro Paladin was statistically lower than Stephens both seasons but trended higher at Lexington except where disease influenced results in 2009 (data not shown). Hence, Agripro Paladin appears most competitive in low precipitation environments.

Variety performance: grain protein concentration

The variety main effect for GPC was highly significant at all site-years (appendices 4.1 and 4.2). Varieties Norwest 553 and Agripro Paladin consistently achieved higher mean GPC than Boundary, although this was not quite significant in all situations (figure 2.6). The mean GPC advantage of these varieties over Boundary ranged from 26 to 70 g kg^{-1} at Pendleton. With the exception of Agripro Paladin at Arlington, mean GPC of these varieties were between 2.8 and 14.7 g kg^{-1} greater than Boundary. The greatest differences in GPC were observed at Arlington, where dryland crown rot interfered with protein accumulation in Boundary. However, it remains unclear why this effect was not more evident at Lexington in 2009, where dryland crown rot also curtailed yield. Comparisons between Norwest 553 and Agripro Paladin were occasionally significant, but were not consistent.

Variety did not appear to substantially influence NUE. Disease incidence in Boundary was responsible for differences at two of three site years showing a significant variety effect. Only at Pendleton in 2009 does this effect appear without the bias of disease, in which case mean NUE_f of Norwest 553 was nearly 14% greater than Boundary.

Overall, varieties performed similar regardless of environment. Norwest 553 demonstrates performance superior to Boundary by coupling high yields with greater GPC. Agripro Paladin also shows improved GPC relative to Boundary but may sacrifice yield to do so. Lower yield may also be associated with Agripro Paladin when compared to Stephens in higher yield environments. While generally not desirable, some sacrifice of yield may be acceptable from a marketing perspective if target GPC levels are obtained more consistently and protein discounts avoided.

Comparisons to recommendations

In this study, N requirements for achieving GPC levels specified in current fertilizer guides varied tremendously. Experimentally derived values are summarized in table 2.4. The high incidence of values above recommendations is notable, particularly at low precipitation locations. However, even within individual site-years requirements both below and above recommendations occurred. Experimental values were generally lowest and most stable at Pendleton which suggests that higher yield environments may in fact be more suitable for HRW production in this region. This is contrary to the traditional belief that low yield, high stress environments like those represented by Lexington and Arlington can produce high GPC most consistently. This is not to say that HRW production is not feasible at low precipitation sites. Lexington 2007 is a clear example of a case where conditions were conducive to average yield and high GPC. Nevertheless, it is clear that low yield and high stress experienced in 2008 and 2009 are not necessarily appropriate conditions for efficiently achieving target GPC.

Due to differences in NUE_f among site years, an additional 7 kg N Mg^{-1} above requirements for yield was not always sufficient to achieve high protein. At Pendleton in 2008, this additional quantity of N was adequate to achieve GPC of at least 120 g kg^{-1}, and was nearly sufficient in 2009. At both Lexington and Arlington, at least double this quantity of N was needed to achieve the same goal in 2008 and 2009. Therefore, this recommendation may only valid where NUE_f of approximately 30% or greater can be expected.

Table 2.4 Current Oregon State University nitrogen recommendations per unit grain production (kg Mg^{-1}) at corresponding grain protein concentration goals (g kg^{-1}) versus experimentally derived values

Protein Goal	Nitrogen Required	Average	**Pendleton**		**Lexington**			**Arlington**
			2008	2009	2007	2008	2009	2009
110	40 - 48	45	35	35	-	51	50	-
120	43 - 53	50	45	55	38	66	70	59
130	47 - 58	55	57	73	53	-	99	114

It is clear that substantial variation in GPC and N requirements occurred among years, much of which is explained by the disparity between NUE_s and NUE_f. Where soil N was sufficient to achieve a particular GPC goal, apparent N requirements were lower than recommendations. This suggests that the underlying NUE assumed in current recommendations is lower than actual NUE_s in these environments. Therefore, where little or no fertilizer N is required, recommendations overestimate required N. This appeared to be the case at Lexington in 2007, since little or no fertilizer N was needed to achieve target GPC. However, recommendations were at least moderately exceeded at Lexington and Arlington in 2009, despite high soil N levels. Late establishment and high stress during this season apparently reduced the ability of wheat to actually acquire this N. As a result of low GPC during the high stress seasons in 2008 and 2009 at Lexington and Arlington, there was actually a positive across-years relationship between yield and GPC at these sites.

Due to low NUE_f at Lexington and Arlington, achieving target GPC by applying large amounts of fertilizer N caused requirements to rapidly and dramatically exceed recommendations. Higher NUE_f at Pendleton was sufficient to reduce the range of observed N requirements relative to low rainfall locations. Nevertheless, a slight reduction in NUE_f forced requirements outside the recommended range in 2009. Revised recommendations should include allowances for differences in NUE_s and NUE_f in different precipitation environments. Alternatively, it may be best to recommend HRW production only when soil N and moisture are high and relatively well distributed in the profile. With a single pre-plant soil test, producers could determine if soil N is sufficient to meet target GPC at experimentally derived levels of NUE_s. Soil moisture accumulated during the fallow year may also help determine if greater N uptake is likely.

Conclusions

Application of fertilizer N significantly impacted both yield and GPC of wheat grown in this study. Nitrogen fertilizer was generally required to optimize yield at Pendleton. Yield loss with increasing N rates was more frequently observed at Lexington and Arlington due to low yield potential and high soil residual N. Grain protein concentration was positively correlated with N fertilizer rate at all site-years. However, the magnitude of response differed substantially between both years and location, underscoring the difficulty of managing N for GPC in this region.

Soil N use efficiency was generally high except where low yield and high N coincided. Fertilizer use efficiency was lowest at Lexington and Arlington, and always significantly lower than NUE_s regardless of site-year. This suggests that applying large quantities of fertilizer N at planting is an inefficient strategy to enhance GPC, particularly in low precipitation environments. Fertilizer applications in the spring of the fallow year may improve fertilizer N throughout the soil profile, and should be investigated for improving NUE_f.

Wheat varieties used in this study differed in terms of both grain yield and GPC, but performance was fairly consistent across site-years. Grain yield was greatest for Norwest 553 and Boundary, whereas best GPC was achieved with either Norwest 553 or Agripro Paladin. All varieties had yield at least as high as the soft white check variety, Stephens, except for Agripro Paladin at Pendleton.

Current recommendations are not adequate for HRW wheat production in this study area. Furthermore, the belief that high stress, low yield environments are more suited to HRW production was generally false in this study. Wheat grown at Pendleton exhibited greater NUE_s and NUE_f, which led to more stable, efficient production of high GPC wheat than at either Lexington or Arlington. Improved recommendations must provide for differences in NUE_s and NUE_f, as well as their tendency to vary between precipitation zones. Regardless of location, HRW production may be most advisable when soil N and moisture are adequate to support average yield and high GPC without large fertilizer inputs.

NITROGEN MANAGEMENT AND VARIETY SELECTION FOR DRYLAND PRODUCTION OF HARD RED WINTER WHEAT IN NORTHEASTERN OREGON: THE USE OF SPRING N APPLICATION AND PLANT TISSUE TESTING FOR IMPROVING NITROGEN MANAGEMENT

Abstract

Proper nitrogen (N) management is important for profitable hard red winter (HRW) wheat production in the dryland growing regions of northeastern Oregon. However, N management for grain yield and protein concentration (GPC) is challenging in these dryland systems due to climate differences between locations and seasonal weather influences. Current practices entail applying nearly all fertilizer N before planting. Delaying a portion of N application until spring could help improve N management decisions for yield, and may be useful for enhancing GPC of hard red winter (HRW) wheat. It is therefore important to understand the efficacy of spring N application and when it may be warranted to improve either yield or GPC**.** This study investigates the effects of fertilizer N rate, N application timing, and location at six site-years in northeastern Oregon from 2007 to 2009. A site at Pendleton represented an intermediate (420mm) precipitation zone and a low precipitation (250-300 mm) zone was represented by sites at Lexington and Arlington, Oregon. Whole plant tissue N concentration (TN) at Zadoks growth stage (GS) 30 and flag leaf nitrogen (FLN) were also evaluated as decision making tools for N management. Spring N caused fewer reductions in yield than fall application when excessive N was harmful to yield at Lexington and Arlington. Spring N significantly improved GPC more effectively than fall N application in one of two years at Pendleton, but had a neutral or negative effect on GPC at Lexington and Arlington. Tissue N at GS 30 was positively correlated with GPC. A critical level of 41 g kg^{-1} at 126 g kg^{-1} GPC was determined across site-years. Flag leaf nitrogen also showed a strong, positive relationship to GPC, but varied considerably among site-years due to environmental influences and time of leaf sample collection.

Introduction

Soft white winter (SWW) wheat is the primary wheat market class produced in Oregon (NASS, 2004-2009). Production of a nontraditional market class such as hard red winter (HRW) wheat has potential to increase grower profits. For grain delivered to Portland, Oregon, higher market value of HRW wheat is generally associated with grain protein concentration (GPC) of 115-125 g kg^{-1} or more. Proper nitrogen (N) management is essential to produce HRW wheat that meets both grain yield and GPC expectations. Grain protein concentration of 125 g kg^{-1} is the standard for millers and bakers (PNW WQC, 2007). Achieving this “target” GPC requires that wheat take up N in excess of yield requirements, which can be achieved with addition of fertilizer N to crops (OSU, 1970).

It may be possible to improve N management for both yield and GPC in northeastern Oregon by applying a portion of fertilizer N in the spring. Currently, producers in this semi-arid region usually apply all fertilizer N during the spring of the fallow season, or banded near the seed at fall planting in no-till systems. Both practices allow N application in conjunction with other field operations, thus minimizing costs. While advantageous from a logistic standpoint, it is extremely difficult to predict crop yield potential before planting due to highly variable growing conditions experienced in this region. As a result, determining a proper N rate is challenging. A given rate may prove either deficient or excessive depending on subsequent growing conditions, especially rainfall. This is of particular concern for HRW wheat production, in which case N deficiency can result in low protein grain with reduced market value. Spring N applications are not routine in this region, but if effective, would allow producers to incorporate evaluations of crop health, plant N status, and moisture conditions into fertilizer decisions.

Previous research with spring N applications has produced mixed results. An extensive study in northeastern Oregon by Hunter et al. (1961) showed that for 91 of 152 sites, there were no was no yield difference between spring and fall N application. However, among remaining sites in the study, spring N produced higher yield at 42 of these and was related to soil depth and moisture. In general, where soil moisture was adequate to support the crop through to maturity, fall N was more effective at improving yield than spring N in shallow soils (<150 cm), but also caused the greatest yield losses at sites where average annual precipitation was less than 380 mm. It was presumed that spring N was less apt to over-stimulate vegetative growth which can prematurely exhaust limited soil moisture, a scenario also described by other researchers (Fowler and Brydon, 1989; McDonald, 1989). Sites with average annual precipitation greater than 380 mm were less represented in the study and deserve further consideration.

Spring N application may also be useful for GPC enhancement of HRW wheat. Spring N significantly increased GPC 8-13 g kg^{-1} for irrigated HRW wheat in southern Idaho (Brown and Petrie, 2006). Studies of N rate and timing in eastern Colorado demonstrated improvement for both yield and GPC with spring N, in which 4 and 35% more fall applied N was necessary to achieve the same GPC achieved with spring application of 22 and 67 kg N ha^{-1}, respectively (Vaughan, 1990). In contrast, Hunter et al. (1961) noted that, on average, slightly more spring N was needed to produce a bushel of grain than fall N in northeastern Oregon. This difference likely stems from the distinct rainfall patterns at these study locations. The high plains of eastern Colorado receive the majority of their rain in the spring and summer, whereas the majority of rainfall occurs between October and April in the PNW. Results from Hunter et al. (1961) showed a trend for high GPC with spring N at low fertilizer rates, but relatively lower GPC at high rates when compared to fall N. This suggests a combination of fall and spring N treatments may maximize both yield and GPC, but studies addressing this hypothesis for northeastern Oregon are lacking.

Regarding additional application of N in the spring, it would be useful to know when a positive yield or GPC response is likely to occur. The wheat plant itself can act as a good indicator for this purpose because tissue N (TN) concentration of aerial plant material reflect the capacity of soil to supply N (Baethgen and Alley, 1989a). Tissue N tests are typically taken at Zadoks growth stage (GS) 30 (Zadoks et al., 1974). This represents a compromise between best predictive ability and allowing enough time for lab analysis and topdressing (Bundy and Andraski, 2004).

A linear relationship between fertilizer N rate for optimum yield and TN at GS 30 has been described for soft red winter wheat (Baethgen and Alley, 1989b; Scharf and Alley, 1993). Also of interest are critical levels, the concentration at which further N additions are unlikely to elicit a positive grain yield response. Critical levels for soft red winter wheat in the eastern United states are well established and range from 35-41 g kg^{-1} (Weisz et al., 2007). Little published research addresses critical values in HRW wheat, with the exception of a study in Colorado, where a critical level of 32 g kg^{-1} was indicated (Vaughan et al., 1990). Besides the relative lack of information for HRW wheat, research has not addressed the relationship of TN and GPC. Given that TN concentration is related to grain yield, it is likely that such a correlation also exists with GPC. Therefore, it may be possible to determine critical levels for achieving target GPC, which would help producers determine when additional N applications could increase the odds of achieving target GPC for HRW wheat. An early season test would be particularly useful to dryland HRW production in the PNW, since the decision to apply fertilizer N could be made while subsequent rainfall for incorporation is still expected.

Flag leaf nitrogen (FLN) concentration is another indicator of plant N status. Research with FLN has generally emphasized sampling when 50% of heads are fully emerged (Brown et al., 2005; Tindall et al., 1995). Sampling prior to heading has the advantage of giving additional time for analysis and decision making, but may positively bias results since FLN typically declines as the plant matures. The FLN test is best suited to determine N sufficiency for GPC, as grain yield is less responsive to N by the time of flag leaf emergence.

Critical levels for FLN are relatively well established for irrigated HRS wheat, in which case minimal response to N may be expected when FLN exceeds 42 g kg^{-1} (Tindall et al., 1995; Wescott et al., 1997). Flag leaf N relations to GPC in HRW wheat are less consistent. Brown and Petrie (2006) reported FLN associated with 120 g kg^{-1} GPC as 43.6 and 45.2 g kg^{-1} in 1985 and 1987, but only 34.5 g kg^{-1} in 1986 for irrigated HRW wheat in southern Idaho. In the nearby Treasure Valley of Oregon, 125 g kg^{-1} GPC was associated with FLN of 38 g kg^{-1}, but GPC only reached its asymptote near 132 g kg^{-1} and FLN of 44 g kg^{-1} (Shock et al., 1986). Little additional research is available concerning FLN in HRW wheat and is conspicuously absent for dryland systems such as those common in northeastern Oregon. Similar to the TN test, FLN may indicate when additional N application at anthesis is warranted.

The primary objective of this research was to evaluate the potential to improve N management for yield and GPC with addition of N in the spring following a range of fall applied N treatments. Because additional N is only warranted where a yield or GPC response is likely, both the TN and FLN were evaluated as prognostic tools for determination of N sufficiency.

Materials and Methods

A detailed description of materials and methods may be found in chapter two of this thesis (pp. 33-37). The following materials and methods pertain exclusively to the particular set of treatments and plant sampling protocols used in this portion of the overall study. Treatments were a factorial arrangement of four wheat varieties, seven fall-applied and two spring-applied N fertilizer rates. Individual treatments were planted in 1.5 x 6 m plots arranged in a randomized complete block design with four replications. Nitrogen treatments were adjusted according to the yield potential of each precipitation zone. Fall fertilizer N rates at Pendleton ranged from 0 to 337 kg N ha^{-1} in 56 kg increments. Corresponding fall N rates at Lexington and Arlington were from 0 to 168 kg N ha^{-1} in 28 kg increments. Spring N treatments were imposed on all but the lowest and highest fall N treatments. At Pendleton, spring fertilizer N rates were either 0 or 56 kg N ha^{-1}. For Lexington and Arlington, these rates were 0 and 28 kg N ha^{-1}. A drill capable of banding fertilizer was unavailable; therefore the seeding drill was used to place fall fertilizer N approximately between and below seeding rows immediately prior to planting at both Lexington and Arlington. At Pendleton, fall fertilizer N was applied in similar fashion approximately one month prior to planting. Spring fertilizer N was surface broadcast using a drop spreader. Nitrogen source for all N applications was granular urea (46-0-0). Potassium magnesium sulfate (K-Mag®, 0-0-21.5-21) was applied in the fall to all plots, regardless of location, at the rate of 13.5 kg S ha^{-1} to eliminate any potential sulfur deficiencies.

Samples of total aboveground plant tissue were collected from 0.5 meters of an inside row near GS 30. Plant tissue was collected from plots receiving only a fall N treatment. Plant tissue was not collected from plots that were to receive spring N. Samples were dried in a heated, forced air dryer for 72 hours. Dry matter weight was recorded and samples analyzed for whole plant N concentration using the Kjeldahl method (Foulk et al., 1952). Flag leaf nitrogen concentration was determined from a pool of ten randomly collected flag leaves per plot. Leaves were dried as per plant tissue samples before whole N concentration analysis using the Kjeldahl method (Foulk et al., 1952).

Plots were harvested at physiological maturity with a Hege small plot combine (Wintersteiger Inc., Salt Lake City, Utah, USA). Grain moisture and test weight were recorded, and reported grain yield was adjusted to 12% moisture. Grain protein concentration was estimated using NIR transmittance spectroscopy with an Infratec™ 1241 Grain Analyzer (Foss Analytical, Slangerupgade, Denmark).

Statistical analyses were performed using SAS statistical software (SAS, 2003). Analysis of variance was performed with the PROC GLM procedure. Least significant difference (LSD) mean separation was performed using the MEANS statement with default significance set at $p \leq 0.05$. Linear and quadratic models were fit to TN and FLN data using the PROC REG procedure. Critical values in Cate-Nelson (Cate and Nelson, 1971) plots were obtained with a modified linear plateau model using the PROC NLIN procedure.

Results and Discussion

Grain yield

The main effect of spring N on yield was never by itself statistically significant for any site-year (appendices 4.7, 4.8). A positive yield response to spring N would have been expected, but soil N levels were sufficiently high that maximum yield was achieved in check plots or with the first increment of fall N at Lexington and Arlington. Although yield was slightly more responsive to N at Pendleton, yield was generally maximized with the first increments of fall N at this site as well. It was only possible to make a comparison in

2009 at the 112 kg N ha^{-1} rate, in which both fall and spring N treatments statistically improved yield over the 56 kg N ha^{-1} treatment (appendix 4.9).

Although the main effect of spring N was not significant, the spring N by total N interaction was significant at both Lexington and Arlington in 2009, and similar trends were evident at Lexington in 2007 (appendix 4.8). This was expressed in higher yield with spring N at low fertilizer rates but with no consistent difference at higher rates. At Arlington, average yield of HRW varieties was 0.1 Mg ha^{-1} greater with spring N treatments when fertilizer N totaled either 56 or 84 kg ha^{-1}, although individual comparisons were not statistically significant (figure 3.1). Similar results were obtained at Lexington in 2009 (appendix 4.10).

Greater yield with spring N is consistent with observations made previously in this region and elsewhere in that yield at these site-years were either static or declined with increasing N (Fowler and Brydon, 1989; Hunter et al., 1961; McDonald, 1989). Unfertilized checks produced the highest yields in these previous studies, which was also the case in our study. Spring N was apparently less likely than fall N to stimulate excessive vegetative growth, which exacerbated terminal drought. A lack of differences with spring N at higher N rates was not surprising given that treatments still emphasized fall application. At total N rates above 84 kg N ha^{-1}, yield loss from fall N was apparently saturated.

Because yields were generally less than average at Lexington and Arlington during this study, little can be said about the relative efficacy of spring N under more optimum conditions. Delaying N fertilization could help reduce the risk of incurring yield loss from over-fertilization in poor years. However, yield was greatest when little or no N was applied at any time. This suggests that if soil N levels are moderate to high producers may do well to forgo fertilization altogether or apply only a low maintenance rate if yield predictions are low due to poor soil moisture.

Grain protein concentration

Analysis of variance indicated that GPC was improved by spring N at Pendleton in 2008 (figure 3.2; appendix 4.9) The greatest increase for spring N was 7 g kg^{-1} at a total N rate of 112 kg h^{-1}. Smaller increases between 2 and 3 g kg^{-1} at higher N rates were observed, but individual comparisons were not statistically significant. In contrast to 2008, both application times produced nearly identical GPC in 2009 at Pendleton.

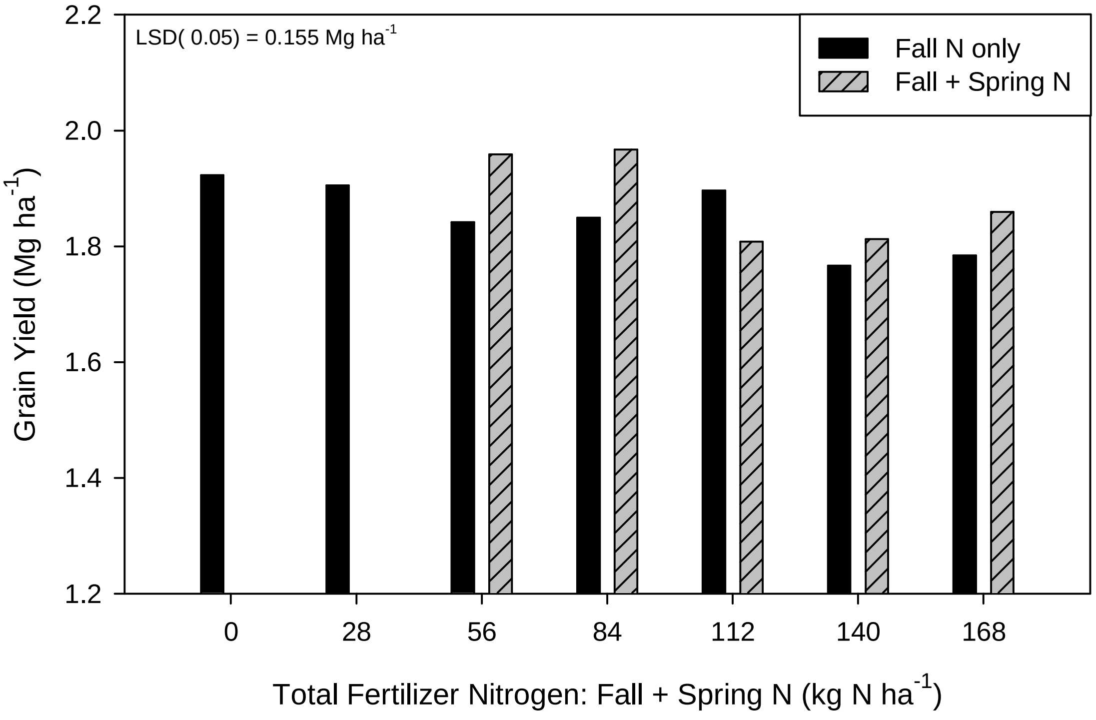

Figure 3.1 Arlington site comparisons of mean yield for fall only versus fall plus spring nitrogen fertilizer treatments in hard red winter varieties

Greater efficacy of spring N in 2008 was likely due to high rainfall in May and June. Total rainfall in these months differed only slightly between years, being 67 mm and 65 mm in 2008 and 2009, respectively. However, the distribution of rainfall was different each year. Nearly 61 mm of the total 67 mm fell between May 15 and June 15 in 2008. Rainfall events were more concentrated in early May of 2009, being more sporadic afterwards. As a result, accumulated rainfall was only 31 mm from May 15 – June 15, 2009. The 77 year average from this period is 42 mm. The large concentration of rainfall just prior to anthesis in 2008 was apparently sufficient for the wetting front to reach spring applied N, resulting in increased N uptake and improved GPC. In chapter two, GPC was more responsive to fertilizer N in 2008 than 2009 at Pendleton. Therefore, availability of fall N may have also been improved by these rainfall events.

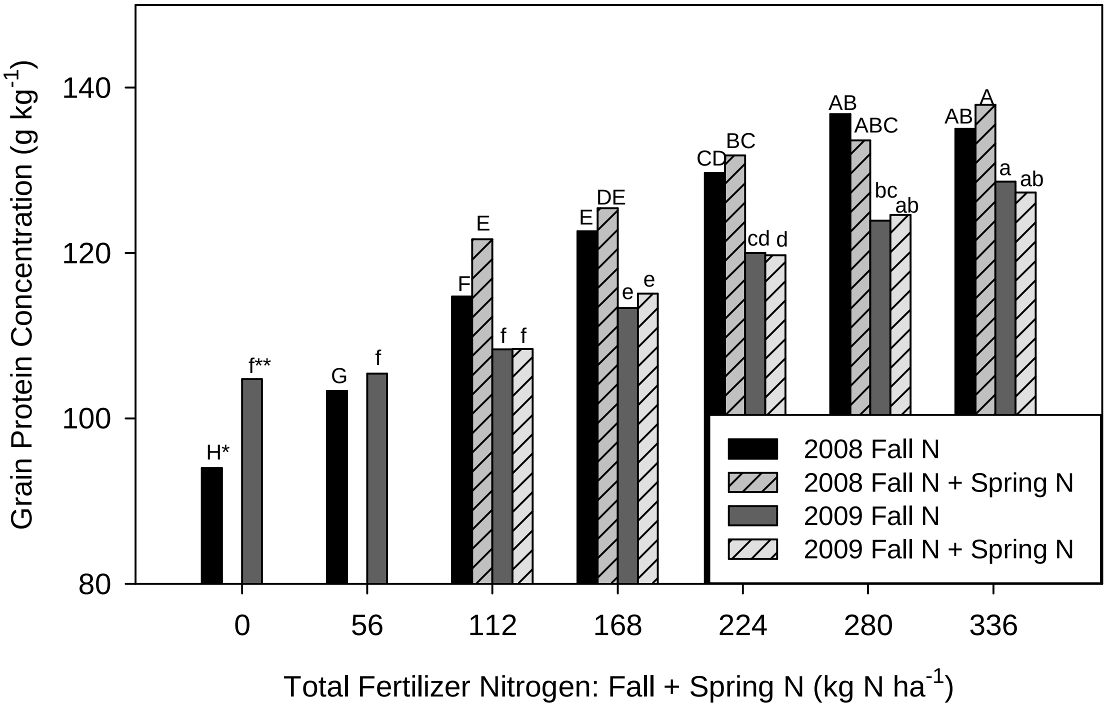

Figure 3.2 Pendleton 2008 and 2009 sites comparisons of mean grain protein concentration (GPC) for fall only versus fall plus spring nitrogen fertilizer treatments in hard red winter varieties
* GPC with same uppercase letter not significantly different ($p \leq 0.05$)
** GPC with same lowercase letter not significantly different ($p \leq 0.05$)

This contrasts with observations by Smika and Greb (1973) showing that GPC never exceeded 123 g kg^{-1} when precipitation approximately during this same period exceeded 48mm across 55 site years. The authors attributed this to an increase in fertile tiller number without a commensurate increase in N uptake, resulting in protein dilution. This does not hold true when significant N and water are simultaneously present (Gregory et al., 1981; Spiertz and Vos, 1983; Wuest and Cassman, 1992b), which appears to have been the case in 2008.

The frequency with which late season rainfall could improve N uptake is difficult to predict. The 2008 and 2009 seasons represented below and above average rainfall during this period, respectively. One may conjecture that, on average, an intermediate response would occur on any given year. However, it is possible that such a response would only occur with exceptionally wet weather during this period. Improving soil moisture to any appreciable depth would require not only above average rainfall, but also the absence of intervening dry periods, allowing time for roots to re-proliferate and acquire N (Brady et al., 1995). Deep profile N can also contribute to improved GPC (Cochran et al., 1978; Lutcher et al., 2007; Smika and Grabouski, 1976). Mineral N below 90 cm was not measured in 2008, but totaled 70 kg ha^{-1} between 90 and 150 cm in 2009 (data not shown) which indicates a lack of deep profile N was not to blame for lower GPC at Pendleton that year.

In contrast to Pendleton, the effect of spring N on GPC was neutral to negative at all low rainfall sites. At Arlington, spring N reduced average GPC compared to fall application. Mean reduction across HRW varieties varied depending on N rate but was particularly high (56 g kg^{-1}) at the 84 kg ha^{-1} total N rate (figure 3.3), the same treatments that resulted in greater grain yield. Therefore, lower GPC resulted from greater protein dilution associated with less yield reduction in spring N treatments. Although not statistically significant, there was a visible trend for slightly lower GPC with spring N at Lexington in 2009. At either site, the fact that spring N slightly reduced yield losses without at least maintaining GPC show that spring N was poorly available for GPC enhancement in 2009. Results from Lexington in 2007 and 2008 show little difference in GPC between spring and fall N applications (appendix 4.10). Therefore, within the context of this study, spring N was at best neutral, and at worst counterproductive for increasing GPC in these low rainfall environments.

Although this study clearly shows spring N utilization was equal to or poorer than fall N at all but one site-year, these results may only pertain to broadcast granular urea, such as used in this study. Ureic fertilizers are susceptible to significant gaseous losses when fertilizer remains on moist surfaces at temperatures greater than 4.4°C, but are minimal when incorporated by rain or irrigation (Bouwmeester et al., 1985; Engle, 2008). Readily available alternatives to dry urea include ammonium sulfate and urea-ammonium nitrate (UAN). These can likewise be broadcast, but superior results have been shown by injection of UAN, likely because this approach increases availability directly in the root zone (Janzen et al., 1991). For example, 50% more N was utilized with point injection versus broadcast UAN to HRW wheat in Kansas at rates of 44 kg ha^{-1} or less (Schlegel et al., 2003). Injection of UAN may also be preferable to broadcast UAN since there is potential to burn foliage with this liquid product (Lutcher and Mahler, 1988). Given the success of point injection for improving fertilizer use efficiency and GPC in other regions, this approach may merit further investigation as a tool for N management of HRW wheat in northeastern Oregon.

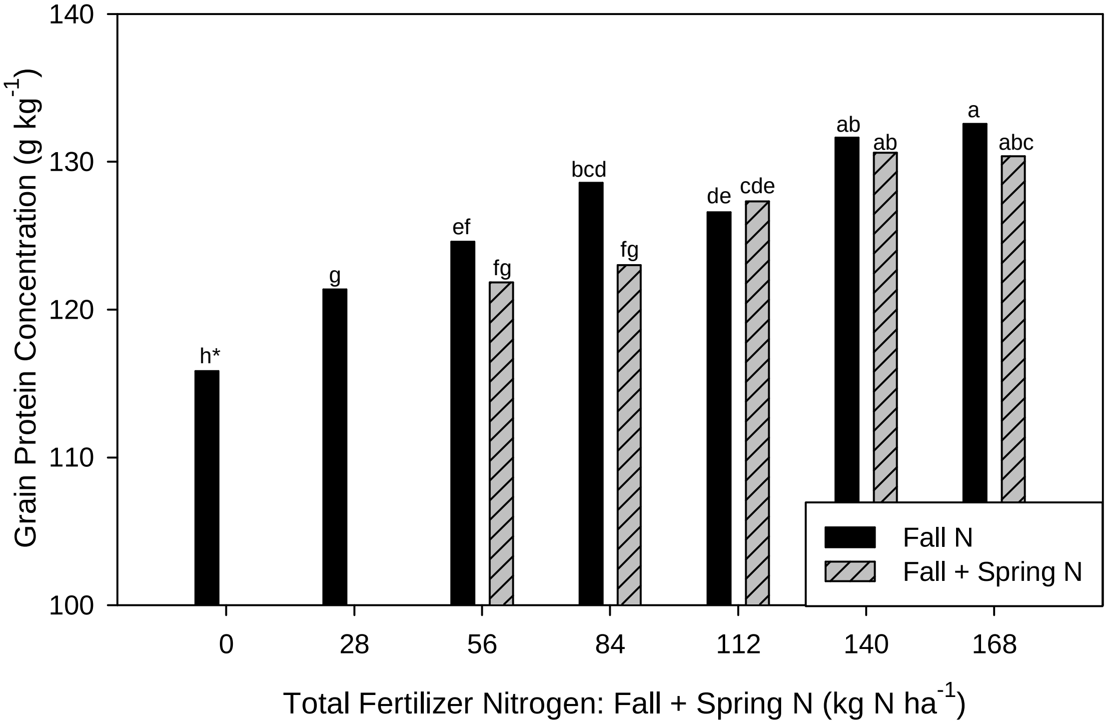

Figure 3.3 Arlington site comparisons of mean grain protein concentration for fall only versus fall plus spring nitrogen fertilizer treatments in hard red winter varieties
* GPC with same letter not significantly different ($p \leq 0.05$)

Growth stage 30 plant tissue nitrogen concentration: grain yield

A positive yield response to N treatments was observed at Pendleton in both seasons, although yield was generally maximized at lower fertilizer N rates due to high residual soil N. Consequently, the range of TN values never extended below 34 g kg^{-1}. Furthermore, very low biomass at sampling in 2008 (170 kg ha^{-1} versus 750 kg ha^{-1} in 2009) resulted in high TN values that were not correlated to treatments (appendix 4.7). Critical TN levels for yield as low as 32 and 35 g kg^{-1} are reported in literature (Baethgen and Alley, 1989b; Vaughan et al., 1990). Hence, given the limited dataset and lack of values in the low range, it was not possible to determine a critical level for yield.

Among other site-years, a positive response to fertilizer N was only observed at Lexington in 2008. Residual soil N was at least sufficient to maximize yield in all other instances. Here, the spectrum of TN values encompassed more low values than at Pendleton but a relationship between TN and yield was nonetheless absent. In order to determine critical values at any of these locations, it will be necessary to locate plots on more N deficient soils.

Growth stage 30 plant tissue nitrogen concentration: grain protein concentration

In general, a strong relationship was observed between TN at GS 30 and GPC in this study. For the same reason of low biomass previously mentioned, TN had a very narrow range (47-57 g kg^{-1}) at Pendleton in 2008, and was only weakly correlated to GPC (figure 3.4). Pendleton 2008 observations were therefore removed, after which Cate-Nelson analysis indicated a critical TN level of 41 g kg^{-1}, which corresponded to 126 g kg^{-1} GPC.

Variation around this critical level occurred among site-years, but was not unexpected given the differences in growing conditions between seasons, among sites, and the potential influence of biomass at sampling. The only aberration of concern came from Pendleton in 2009. However, with only one year of meaningful data from this site, it is difficult to conjecture whether the Pendleton 2009 data represents a more extreme case of seasonal variation or if environment specific calibration is necessary. Therefore, a TN critical level 41 g kg^{-1} likely represents a good starting point for producers to use when determining if spring N is warranted to improve GPC. Importantly, these findings represent the first use of TN at GS 30 to predict GPC rather than yield alone. Furthermore, the critical level determined in this study is advantageous since it corresponds approximately to target GPC and not a higher, less economical goal. While only a limited number of site-years contributed to these observations, the strong relationship seen here merits further research to validate stability of this critical value across years and environments.

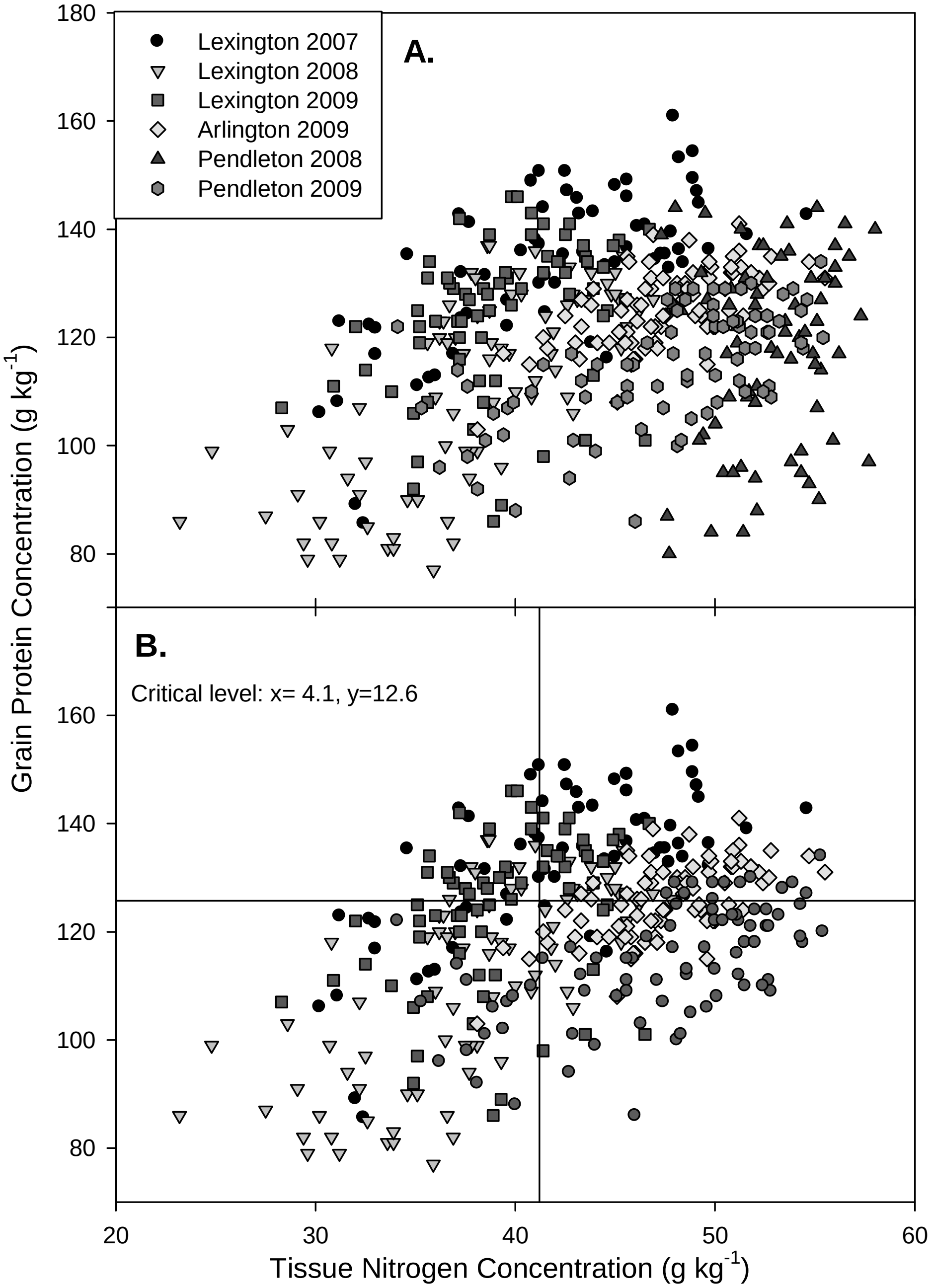

Figure 3.4 The relationship of Zadoks growth stage 30 tissue nitrogen concentration to grain protein concentration for all site-years combined (A), and all site years minus Pendleton 2008 with accompanying Cate-Nelson quadrants (B)

Flag leaf nitrogen

Flag leaf nitrogen was highly correlated with GPC at all site-years where flag leaves were collected. Flag leaves were not collected at Lexington and Arlington in 2009. Differences between the remaining site-years were evident and were generally of a greater magnitude than observed for TN data. Separating data by site helped clarify this relationship (figure 3.5).

Combining data from Lexington 2007 and 2008 created a reasonable profile of FLN and GPC. A quadratic model explained 57% of variance, and the regression equation estimates target GPC at 33 g kg^{-1} FLN. This clearly shows that FLN can be used to predict GPC in these low precipitation environments, although flag leaf N at target protein was lower than values previously reported for either spring or winter wheat (Brown and Petrie, 2006; Tindall et al., 1995; Wescott et al., 1997). This is not surprising given that leaves were collected shortly after anthesis in both years at Lexington. Flag leaf N generally decreases from emergence towards maturity (Brown et al., 2005; Tindall et al., 1995), and was shown to decline 9-13 g kg^{-1} in the short time between 50% heading and anthesis in studies by Brown and Petrie (2006). A critical level corresponding to post-anthesis FLN may not be useful in a production situation since little time would remain to process samples and apply fertilizer while plants are still responsive to N. Nevertheless, the strong relationship seen here sets a precedent for further research of the FLN test in these environments.

There was also a strong correlation between FLN and GPC at Pendleton, but this relationship was different each year. For every 10 g kg^{-1} rise in FLN, GPC increased 30 g kg^{-1} in 2008, but only 18 g kg^{-1} in 2009. As a result, regression equations estimate target GPC at 38 and 47 g kg^{-1} FLN in 2008 and 2009, respectively.

Sampling time again helped explain these results. Flag leaves were collected at late boot stage in 2008, immediately prior to the series of rains that improved late season N uptake. Improved uptake can actually increase FLN temporarily (Tindall et al., 1995). Had collection taken place at anthesis in 2008, after more N would have presumably been acquired, levels for target GPC would most certainly have increased. On an

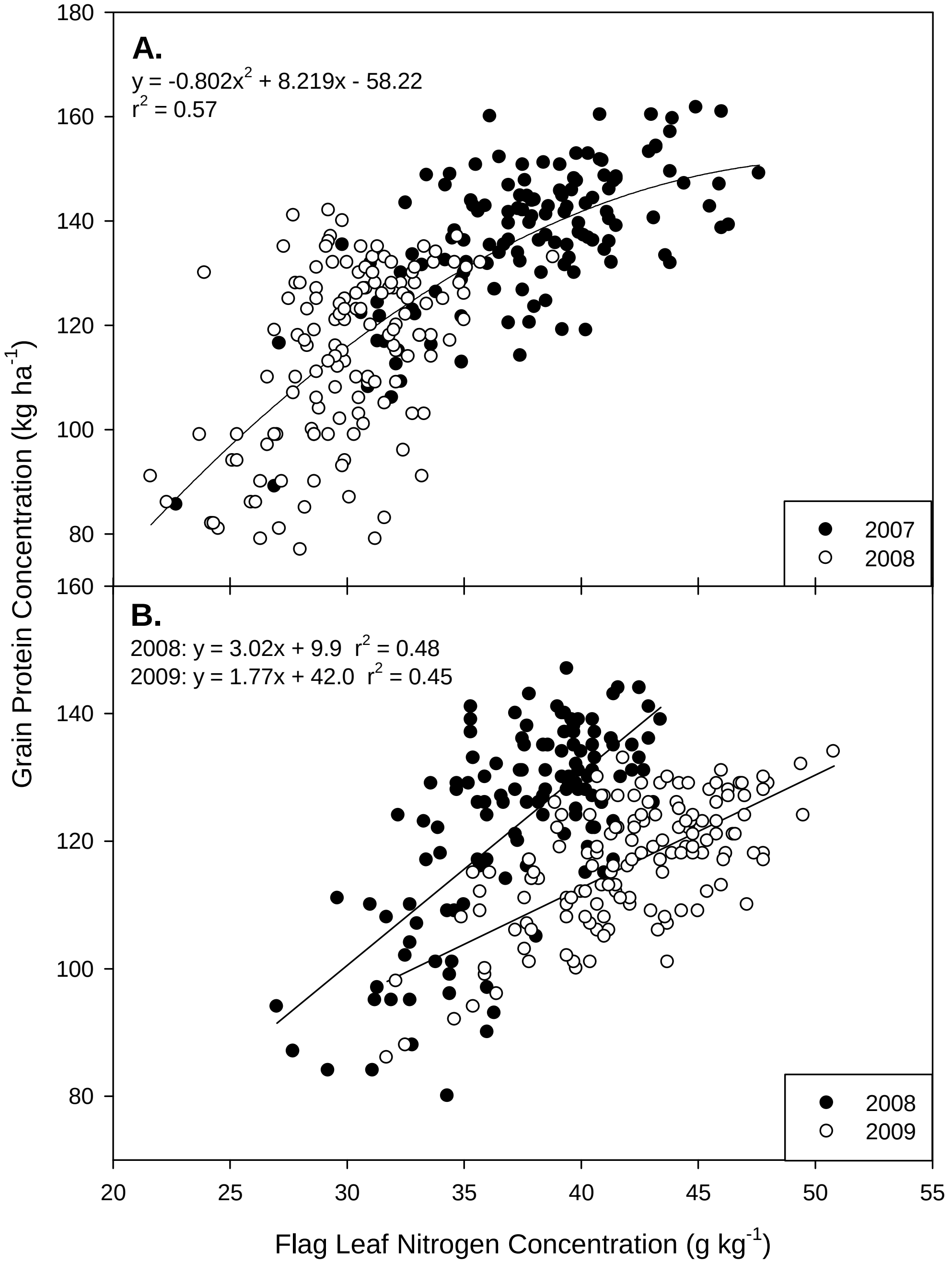

Figure 3.5 The relationship of flag leaf nitrogen concentration to grain protein concentration at Lexington (A) and Pendleton (B)

opposite note, only very high FLN were associated with target protein in 2009 since soil N was apparently less available as a source for grain protein synthesis.

Given the contrasting scenarios observed at Pendleton and the low FLN at Lexington, it was not possible to determine any sort of reliable critical FLN level. However, the fact that a strong, positive correlation between FLN and GPC was demonstrated suggests development of a reasonable critical level may be possible given more adequate datasets.

The efficacy of foliar N sprays to actually enhance GPC at various levels of FLN must also be evaluated in these environments if the FLN test is to be of use for N management. Concentrated foliar N solutions applied at flowering can significantly improve GPC (Bly and Woodard, 2003; Finney et al., 1957) and may be the only viable option to improve late season plant N status without the use of irrigation to incorporate N. However, foliar sprays can cause varying degrees of leaf burn that may reduce yield in some instances (Bly and Woodard, 2003) Even if FLN were not used for actual N management decisions, its use may have other applications. For example, the FLN test could help with marketing decisions by allowing producers to estimate the value of their crop well before harvest. Additionally, profit margins could be improved by using FLN to identify field regions likely to meet target GPC, followed by segregation of this grain at harvest.

Conclusions

Applying a portion of fertilizer N in the spring influenced yield and GPC differently according to both year and location. Spring N at Pendleton improved GPC as effectively as fall N one year, and more effectively than fall N when cumulative rainfall between late boot stage and the beginning of grain fill was sufficient to support continued uptake of fertilizer N. Hence, spring N application may be useful for correcting N deficiency and enhancing GPC in intermediate precipitation environments. At Lexington and Arlington, spring N application limited yield loss where high N rates caused crops to ‘hay off’. However, this resulted in lower GPC for spring N treatments at two site-years and spring

N never proved more effective than fall N for GPC enhancement in these low precipitation environments.

Whole plant tissue N concentration at GS 30 is a promising tool for N management as it was highly correlated to GPC at all sites where sufficient biomass was available at sampling. Cate-Nelson models indicate critical TN of 41 g kg^{-1} at 126 g kg^{-1} GPC. Producers could use this value to determine when additional N may be warranted to achieve target protein. This test may be most useful for intermediate precipitation environments similar to Pendleton since GPC response to spring N was poor at the low precipitation sites of Lexington and Arlington. However, this does not preclude the possibility of more positive responses to spring N in years with average to above-average precipitation in low precipitation environments. Likewise, the use of point injection and N sources less susceptible to volatile losses may improve NUE and should be explored.

Flag leaf N concentration may also be a useful for predicting GPC. Although differences in sampling time did not allow for determination of a critical level, a strong relationship between FLN and GPC in both precipitation zones indicates this test could be further developed. Future research should emphasize consistent sampling at an earlier growth stage, such as 50% heading, while concurrently exploring the efficacy of foliar N sprays to assist in achieving target GPC when FLN indicates a possible N deficiency.

GENERAL CONCLUSIONS

Hard red winter (HRW) wheat production offers dryland producers in northeastern Oregon an opportunity to capture greater profits than typically possible with soft white winter (SWW) wheat. To benefit from higher prices producers must achieve high yields while meeting market expectations for grain protein concentration (GPC). Greater rates of nitrogen (N) fertilizer are often necessary to meet target GPC of 125 g kg^{-1}. However, seasonal weather and other environmental factors can result in failure to meet market expectations. Improved N management practices and selection of varieties expressing both high yield and GPC are necessary to mitigate this risk while improving farm profitability.

The dryland wheat growing region of northeastern Oregon encompasses multiple environments differing in annual precipitation, growing season length, soil type, and other characteristics. Current fertilizer guides recommend similar fertilizer N rates across these environments and were developed with relatively little information from HRW wheat production. Nitrogen management for high GPC HRW therefore deserves reevaluation.

Fertilizer N was necessary to optimize yield at Pendleton, but decreased yield in several instances at Lexington and Arlington. Fertilizer N always increased GPC, although this effect was due at least partially to yield reduction in two years at Lexington and Arlington. Overall, there were site-years conducive to high GPC and others that were not. This highlights the difficulty of consistently growing high GPC HRW wheat in these environments. Nevertheless, this study identifies some situations that are more suitable for HRW production, and those which are less suitable.

Soil N use efficiency (NUE_s) was quite high at most site-years, but fertilizer N use efficiency (NUE_f) was always much lower, particularly at Lexington and Arlington. Therefore, applying large amounts of fertilizer N at planting was not an efficient means of enhancing GPC. However, moderately higher values for both NUE_s and NUE_f at Pendleton meant high yield and target GPC was possible at more reasonable N rates in this environment. This contrasts with previously held beliefs that HRW production is best suited to low yield, high stress environments. High NUE_s was attributed to more uniform distribution of this N source with soil moisture in the profile compared to fertilizer N. Nitrogen application during the spring of the fallow year may improve distribution of fertilizer N to better match that of the soil N profile. Future studies should evaluate both this method and banding N at planting, the latter of which was used in this study.

As a result of the different NUE between soil and fertilizer N pools, a reevaluation of current N recommendations may be necessary. The assumption in current fertilizer guides that NUE_s and NUE_f are equal resulted in the under and overestimation of N needs in this study. While accounting for these differences would improve the accuracy of N recommendations, it also suggests that HRW production is only economical where soil N can meet most or all of crop N demands for both yield and protein and soil moisture is sufficient to support recovery of this N. Less than average moisture conditions appear least conducive to both high yield and GPC since this limits N supply to plants.

Concerning varieties, Norwest 553 and Boundary produced the greatest yield, but Norwest 553 and Agripro Paladin outperformed Boundary in terms of high GPC. These represent only a portion of commercially available cultivars, but demonstrate that current varieties vary in their performance for yield and GPC, and selection of a proper variety will be important to the success or failure of a given crop to meet producer expectations.

The usefulness of spring N applications was largely dependent upon the precipitation received at each location. The effect of spring N on yield could not be determined at Pendleton, but was less damaging to yield than fall N at both Lexington and Arlington when N was excessive. Spring N significantly improved GPC at Pendleton in 2008 following significant rainfall from late booting through early grain fill. Spring N was equivalent to fall N for GPC enhancement the following year. These two years of results indicate producers in the intermediate rainfall environments could use spring application to correct N deficiency and that GPC may actually be enhanced in some years. In contrast, spring N produced equal or lower GPC compared to fall N at Lexington and Arlington. While it is possible that spring N could have a more positive impact on GPC in these environments when precipitation is average or greater, it was clearly not advantageous for GPC enhancement in the high stress years of this study. Regardless of location, NUE_f of spring N might be improved with point injection or use of less volatile N sources; both of which deserve further consideration.

Use of tissue N (TN) concentration at Zadoks growth stage (GS) 30 shows promise as a decision making tool for N management. A critical level of 41 g kg^{-1} at 126 g kg^{-1} GPC was calculated from multiple site-years and is likely a good starting point for determining when additional N is needed to meet target GPC. Tissue N at GS 30 is a novel test for this region, particularly regarding prediction of GPC. Therefore, further research should be conducted to validate the consistency of this critical level and whether adjustments are necessary. Flag leaf N (FLN) concentration was also highly correlated with GPC, but datasets were not adequate to determine a critical level. Future research to ascertain such a value should emphasize consistent sample collection time, preferably at 50% heading. The efficacy of foliar N sprays to enhance GPC in these study environments will also need evaluation if FLN is to be effectively used for N management.

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APPENDIX

Table 4.1 Mean squares from analysis of variance for yield (Mg ha^{-1}), test weight (kg hl^{-1}), straw mass (Mg ha^{-1}), grain protein concentration (GPC: g kg^{-1}), nitrogen harvest index (NHI), and fertilizer use efficiency (NUE$_f$) at Pendleton

Source of variation	df	Grain yield		Test weight		Straw mass		df[†]	GPC		NHI		NUE$_f$[‡]	
Pendleton 2008														
N Rate	6	1.07	***	43.5	***	0.59	ns	6	2819	***	0.0020	***	0.0398	ns
Variety	3	0.66	ns	160.7	***	4.58	***	2	398	***	0.0016	**	0.0286	ns
N Rate x Variety	18	0.32	ns	1.8	ns	0.50	ns	12	76	ns	0.0006	ns	0.0136	ns
Block	3	0.78	*	7.1	**	0.54	ns	3	42	ns	0.0027	***	0.0939	**
Pendleton 2009														
N Rate	6	3.40	***	14.3	***	6.55	***	6	1030	***	0.0055	***	0.0461	*
Variety	3	1.75	***	100.5	***	2.98	***	2	296	***	0.0050	***	0.0880	**
N Rate x Variety	18	0.20	ns	0.8	**	0.20	ns	12	39	ns	0.0008	*	0.0291	ns
Block	3	0.04	ns	0.4	ns	0.13	ns	3	26	ns	0.0001	ns	0.0092	ns

*,**,*** Significant at $p \leq 0.10$, $p \leq 0.05$, and $p \leq 0.01$, respectively; ns = not significant

[†] Mean squares for GPC, NHI and NUE$_f$ only pertain to hard red winter varieties

[‡] N Rate and N Rate x Variety degrees of freedom = 5 and 10, respectively for NUE$_f$

Table 4.2 Mean squares from analysis of variance for yield (Mg ha^{-1}), test weight (kg hl^{-1}), straw mass (Mg ha^{-1}), grain protein concentration (GPC: g kg^{-1}), nitrogen harvest index (NHI), and fertilizer use efficiency (NUE$_f$) at Lexington and Arlington

Lexington 2007														
Source of variation	df	Grain yield		Test weight		Straw mass		df†	GPC		NHI		NUE$_f$‡	
N Rate	6	1.00	***	15.4	***	-	-	6	1039	***	-		-	
Variety	3	0.83	**	125.3	***	-	-	2	907	***	-		-	
N Rate x Variety	18	0.16	ns	2.3	ns	-	-	12	65	ns	-		-	
Block	3	1.14	***	25.0	***	-	-	3	1041	***	-		-	
Lexington 2008														
N Rate	6	0.32	**	3.4	***	0.14	ns	6	3574	***	0.0040	ns	0.0421	***
Variety	3	0.91	***	45.3	***	0.68	*	2	929	***	0.0032	ns	0.0168	ns
N Rate x Variety	18	0.10	ns	1.0	***	0.20	ns	12	35	ns	0.0009	ns	0.0021	ns
Block	3	0.01	ns	0.5	ns	0.35	ns	3	12	ns	0.0004	ns	0.0042	ns

*,**,*** Significant at $p \leq 0.10$, $p \leq 0.05$, and $p \leq 0.01$, respectively; ns = not significant

[†] Mean squares for GPC, NHI and NUE$_f$ only pertain to hard red winter varieties

[‡] N Rate and N Rate x Variety degrees of freedom = 5 and 10, respectively for NUE$_f$

Table 4.2 (continued)

Lexington 2009		Grain yield		Test weight		Straw mass		df[†]	GPC		NHI		NUE_f[‡]	
N Rate	6	0.28	ns	2.0	ns	0.19	ns	6	1129	***	0.0008	ns	0.0346	ns
Variety	3	0.60	**	113.2	***	0.02	ns	2	424	***	0.0055	**	0.0902	**
N Rate x Variety	18	0.22	ns	1.5	ns	0.24	*	12	84	ns	0.0007	ns	0.0318	ns
Block	3	1.69	***	7.5	***	0.51	**	3	415	***	0.0111	***	0.0153	ns
Arlington 2009														
N Rate	6	0.08	**	3.2	ns	0.07	ns	6	370	***	0.0035	ns	0.0223	***
Variety	3	2.02	***	214.2	***	0.27	**	2	110	***	0.0135	***	0.0729	***
N Rate x Variety	18	0.04	ns	1.4	ns	0.12	**	12	21	ns	0.0034	ns	0.0043	ns
Block	3	0.03	ns	4.1	ns	0.18	*	3	30	ns	0.0027	ns	0.0010	ns

*,**,*** Significant at p≤0.10, p≤0.05, and p≤0.01, respectively; ns = not significant

[†] Mean squares for GPC, NHI and NUE_f only pertain to hard red winter varieties

[‡] N Rate and N Rate x Variety degrees of freedom = 5 and 10, respectively for NUE_f

Table 4.3 Mean squares of treatment and year effects for two years at Pendleton for yield (Mg ha^{-1}), test weight (kg hl^{-1}), straw mass (Mg ha^{-1}), grain protein concentration (GPC: g kg^{-1}), nitrogen harvest index (NHI), and fertilizer use efficiency (NUE$_f$)

Source of variation	df	Grain yield		Test weight		Straw mass		df†	GPC		NHI		NUE$_f^{\ddagger}$	
N Rate (NR)	6	3.81	***	52.4	***	4.93	***	6	3454	***	0.0063	***	0.0669	**
Variety (V)	3	1.99	***	255.3	***	7.41	***	2	615	***	0.0056	***	0.0245	ns
Year (Y)	1	1.64	**	398.6	***	49.94	***	1	798	***	0.0043	***	0.0112	ns
NR x Y	6	0.55	*	7.0	***	1.97	***	6	387	***	0.0013	**	0.0183	ns
NR x V	18	0.31	ns	1.5	ns	0.35	ns	12	47	ns	0.0006	ns	0.0281	ns
V x Y	3	0.32	ns	8.8	***	0.19	ns	2	32	ns	0.0003	ns	0.0900	**
NR x V x Y	18	0.22	ns	1.2	ns	0.38	ns	12	68	*	0.0009	**	0.0146	ns
Block	3	0.41	ns	3.8	**	0.33	ns	3	35	ns	0.0016	ns	0.0516	*

*,**,*** Significant at $p \leq 0.10$, $p \leq 0.05$, and $p \leq 0.01$, respectively; ns = not significant

† Mean squares for GPC, NHI and NUE$_f$ only pertain to hard red winter varieties

‡ NUE$_f$ degrees of freedom = 5 for NR and NR x Y effects, and 10 for NR x V and NR x V x Y interactions

Table 4.4 Means and comparisons for yield (Mg ha^{-1}), test weight (kg hl^{-1}), straw mass (Mg ha^{-1}), grain protein concentration (GPC: g kg^{-1}), nitrogen harvest index (NHI), and fertilizer use efficiency (NUE$_f$) at Pendleton

Pendleton 2008												
N Rate kg ha^{-1}	Grain yield		Test weight		Straw mass		GPC[†]		NHI		NUE$_f$	
0	5.60	b*	78.9	ab	5.06	b	94	f	0.89	ab	0.77[‡]	
56	5.97	ab	79.1	a	5.29	ab	103	e	0.90	a	0.29	ab
112	6.35	a	78.0	bc	5.43	ab	115	d	0.89	ab	0.39	a
168	6.31	a	77.7	c	5.28	ab	123	c	0.89	ab	0.32	ab
225	6.38	a	75.6	d	5.70	a	130	b	0.87	bc	0.28	ab
281	6.09	a	74.4	d	5.53	ab	137	a	0.86	c	0.24	b
337	6.32	a	75.0	d	5.33	ab	135	ab	0.88	b	0.20	b
LSD (0.05)	0.44		1.1		0.49		6		0.02		0.15	
Pendleton 2009												
0	5.35	d	80.8	a	3.06	d	105	d	0.90	a	0.80	
56	6.21	c	80.8	a	3.94	c	105	d	0.89	a	0.37	a
112	6.56	ab	80.4	ab	4.35	b	108	d	0.89	a	0.30	ab
168	6.73	a	80.2	b	4.69	a	113	c	0.87	b	0.29	ab
225	6.50	abc	79.5	c	4.81	a	120	b	0.85	c	0.23	b
281	6.57	ab	79.1	c	4.75	a	124	b	0.85	c	0.23	b
337	6.28	bc	78.3	d	4.72	a	129	a	0.85	c	0.17	b
LSD (0.05)	0.31		0.5		0.29		5		0.02		0.13	

* Means followed by the same letter not statistically different at $p \leq 0.05$

[†] Means for GPC, NHI and NUE$_f$ only pertain to hard red winter varieties

[‡] NUE$_f$ value for N rate of zero pertains to nitrogen uptake efficiency from the soil only, and is not statistically compared to actual fertilizer use efficiencies.

Table 4.5 Mean squares of treatment and year effects from analysis of variance for two years at Lexington for yield (Mg ha^{-1}), test weight (kg hl^{-1}), straw mass (Mg ha^{-1}), grain protein concentration (GPC: g kg^{-1}), nitrogen harvest index (NHI), and fertilizer use efficiency (NUE$_f$)

Source of variation	df	Grain yield		Test weight		Straw mass		df[†]	GPC		NHI		NUE$_f$[‡]	
N Rate (NR)	6	0.68	***	10.5	***	0.06	ns	6	4848	***	0.0027	ns	0.1168	***
Variety (V)	3	1.80	***	273.7	***	0.35	ns	2	1373	***	0.0054	*	0.1335	***
Year (Y)	2	14.95	***	555.9	***	6.62	***	2	11276	***	0.0005	ns	0.7933	***
NR x Y	12	0.53	***	4.8	***	0.31	ns	12	349	***	0.0019	ns	0.1126	***
NR x V	18	0.10	ns	2.1	*	0.25	ns	12	37	ns	0.0006	ns	0.0145	ns
V x Y	6	0.30	ns	8.0	***	0.22	ns	4	448	***	0.0038	ns	0.1869	***
NR x V x Y	36	0.17	ns	1.3	ns	0.21	ns	24	75	ns	0.0010	ns	0.0123	ns
Block	3	0.94	***	11.0	***	0.44	*	3	489	***	0.0057	**	0.0083	ns

*,**,*** Significant at p≤0.10, p≤0.05, and p≤0.01, respectively; ns = not significant

[†] Mean squares for GPC, NHI and NUE$_f$ only pertain to hard red winter varieties

[‡] NUE$_f$ degrees of freedom = 5 for NR and NR x Y effects, and 10 for NR x V and NR x V x Y interactions

Table 4.6 Means and comparisons for yield (Mg ha^{-1}), test weight (kg hl^{-1}), straw mass (Mg ha^{-1}), grain protein concentration (GPC: g kg^{-1}), nitrogen harvest index (NHI), and fertilizer use efficiency (NUE$_f$) at Lexington and Arlington

N Rate kg ha^{-1}	Grain yield		Test weight		Straw Mass		GPC[†]		NHI		NUE$_f$	
Lexington 2007												
0	3.32	a	78.4	a	-		119	e	-		-	
28	3.19	ab	78.4	a	-		126	de	-		-	
56	2.82	c	77.2	bc	-		136	bc	-		-	
84	2.87	bc	78.3	ab	-		133	cd	-		-	
112	2.75	c	76.5	c	-		141	ab	-		-	
140	2.68	c	76.4	c	-		148	a	-		-	
168	2.67	c	76.5	c	-		140	bc	-		-	
LSD (0.05)	0.34		1.2				8					
Lexington 2008												
0	2.20	bc	81.6	c	1.92	a	88	e	0.86	ab	0.69[‡]	
28	2.34	ab	82.1	b	1.99	a	88	e	0.87	ab	0.16	c
56	2.48	a	82.5	a	1.86	a	107	d	0.89	a	0.29	a
84	2.37	ab	82.1	b	1.83	a	116	c	0.86	ab	0.25	ab
112	2.26	ab	81.9	bc	1.84	a	123	b	0.87	ab	0.18	bc
140	2.01	c	81.9	bc	1.78	a	127	a	0.82	b	0.12	c
168	2.27	ab	81.2	d	2.04	a	130	a	0.84	b	0.16	c
LSD (0.05)	0.24		0.4		0.39		5		0.04		0.08	

* Means followed by the same letter not statistically different at $p \leq 0.05$

[†] Means for GPC, NHI and NUE$_f$ only pertain to hard red winter varieties

[‡] NUE$_f$ value for N rate of zero pertains to nitrogen uptake efficiency from the soil only, and is not statistically compared to actual fertilizer use efficiencies.

Table 4.6 (continued)

Lexington 2009

N Rate kg ha^{-1}	Grain yield		Test weight		Straw Mass		GPC[†]		NHI		NUE$_f$	
0	2.49	a	80.1	a	1.54	a	105	d	0.84	a	0.53[†]	
28	2.22	abc	79.5	ab	1.37	a	118	c	0.85	a	-0.08	b
56	2.42	ab	79.2	b	1.57	a	117	c	0.81	a	0.10	a
84	2.18	abc	79.1	b	1.47	a	127	b	0.85	a	0.01	ab
112	2.10	bc	79.3	ab	1.35	a	131	ab	0.84	a	0.00	ab
140	2.38	abc	79.0	b	1.64	a	133	ab	0.82	a	0.07	a
168	2.06	c	79.0	b	1.37	a	137	a	0.85	a	0.01	ab
LSD (0.05)	0.35		0.8		0.30		8		0.03		0.13	
Arlington 2009												
0	2.01	a	77.9	a	1.12	b	116	f	0.85	a	0.53	
28	1.93	ab	78.0	a	1.22	ab	121	e	0.84	ab	0.19	a
56	1.88	ab	76.8	b	1.19	ab	125	de	0.83	ab	0.11	b
84	1.85	b	77.3	ab	1.11	b	129	bc	0.84	ab	0.10	b
112	1.92	ab	77.6	ab	1.26	ab	127	cd	0.82	ab	0.09	b
140	1.81	b	77.1	ab	1.34	a	132	ab	0.80	b	0.09	b
168	1.81	b	77.6	ab	1.25	ab	133	a	0.80	b	0.06	b
LSD (0.05)	0.14		1.0		0.20		4		0.04		0.06	

* Means followed by the same letter not statistically different at $p \leq 0.05$

[†] Means for GPC, NHI and NUE$_f$ only pertain to hard red winter varieties

[‡] NUE$_f$ value for N rate of zero pertains to nitrogen uptake efficiency from the soil only, and is not statistically compared to actual fertilizer use efficiencies.

Table 4.7 Mean squares for fall and fall plus spring nitrogen treatments from analysis of variance for yield (Mg ha^{-1}), test weight (kg hl^{-1}), straw mass (Mg ha^{-1}), grain protein concentration (GPC: g kg^{-1}), nitrogen harvest index (NHI), fertilizer use efficiency (NUE$_f$), and tissue nitrogen concentration at Zadoks growth stage 30 (TN: g kg^{-1}) at Pendleton

Pendleton 2008														
Source of Variation	df	Grain yield		Test weight		df[†]	GPC		NUE$_f$		FLN		TN[‡]	
Tot. N Rate	4	0.28	ns	49.9	***	4	1205	***	0.145	***	57.5	***	4.2	ns
Variety (V)	3	2.13	***	348.6	***	3	394	***	0.010	ns	61.1	***	99.7	***
Spring N	1	0.06	ns	4.9	ns	1	101	*	0.019	ns	0.9	ns	-	-
Tot. N x V	12	0.49	ns	3.3	ns	8	20	ns	0.005	ns	2.1	ns	4.9	ns
Tot. N x Sp. N	4	0.06	ns	7.5	*	4	61	*	0.005	ns	0.4	ns	-	-
Var. x Sp. N	3	0.23	ns	1.9	ns	3	26	ns	0.005	ns	15.0	**	-	-
Tot. N x Sp. N x V	12	0.08	ns	1.6	ns	8	57	*	0.007	ns	1.7	ns	-	-
Block	3	0.79	ns	11.0	**	3	80	*	0.078	***	7.4	ns	17.6	***
Pendleton 2009	df													
Tot. N Rate	4	0.43	***	23.9	***	4	1409	***	0.037	***	79.6	***	299.8	***
Variety (V)	3	2.16	***	165.8	***	3	192	***	0.051	***	32.5	***	55.7	***
Spring N	1	0.01	ns	0.1	ns	1	0	ns	0.001	ns	8.6	ns	-	-
Tot. N x V	12	0.13	ns	1.1	**	8	9	ns	0.007	**	3.1	ns	2.2	ns
Tot. N x Sp. N	4	0.25	*	0.7	ns	4	8	ns	0.002	ns	2.3	ns	-	-
Var. x Sp. N	3	0.02	ns	0.8	ns	3	7	ns	0.000	ns	17.4	**	-	-
Tot. N x Sp. N x V	12	0.17	ns	0.5	ns	8	11	ns	0.002	ns	5.4	ns	-	-
Block	3	0.23	ns	0.9	ns	3	2	ns	0.007	*	72.8	***	37.1	***

*,**,*** Significant at $p \leq 0.10$, $p \leq 0.05$, and $p \leq 0.01$, respectively; ns = not significant

[†] Mean squares for GPC, NHI and NUE$_f$ only pertain to hard red winter varieties

[‡] Degrees of freedom for Tot. N Rate = 6, and Tot. N x V = 12

Table 4.8 Mean squares for fall and fall plus spring nitrogen treatments from analysis of variance for yield (Mg ha^{-1}), test weight (kg hl^{-1}), straw mass (Mg ha^{-1}), grain protein concentration (GPC: g kg^{-1}), nitrogen harvest index (NHI), fertilizer use efficiency ($NUE_{f:}$ %), and tissue nitrogen concentration at Zadoks growth stage 30 (TN: g kg^{-1}) at Lexington and Arlington

Lexington 2007														
Source of Variation	df	Grain yield		Test weight		df[†]	GPC		NUE_f		FLN		TN[‡]	
Tot. N Rate	4	0.34	ns	17.9	***	4	665	***	-	-	-	-	140.7	***
Variety (V)	3	0.55	**	206.2	***	3	858	***	-	-	-	-	359.4	***
Spring N	1	0.35	ns	0.5	ns	1	20	ns	-	-	-	-	-	-
Tot. N x V	12	0.34	ns	2.2	ns	8	64	ns	-	-	-	-	14.1	ns
Tot. N x Sp. N	4	0.25	ns	5.7	**	4	118	ns	-	-	-	-	-	-
Var. x Sp. N	3	0.12	ns	1.0	ns	3	67	ns	-	-	-	-	-	-
Tot. N x Sp. N x Var	12	0.15	ns	2.7	ns	8	21	ns	-	-	-	-	-	-
Block	3	1.78	***	23.5	***	3	752	***	-	-	-	-	14.6	ns
Lexington 2008														
Tot. N Rate	4	0.66	***	8.1	***	4	2480	***	0.072	***	20.0	***	272.3	***
Variety (V)	3	2.09	***	71.2	***	3	1536	***	0.073	***	15.9	**	77.7	***
Spring N	1	0.04	ns	0.1	ns	1	15	ns	0.003	ns	4.3	ns	-	-
Tot. N x V	12	0.14	ns	0.6	**	8	89	***	0.006	ns	6.5	ns	5.3	ns
Tot. N x Sp. N	4	0.41	**	0.4	ns	4	40	ns	0.012	**	4.3	ns	-	-
Var. x Sp. N	3	0.16	ns	0.5	ns	3	63	ns	0.004	ns	1.8	ns	-	-
Tot. N x Sp. N x V	12	0.13	ns	0.4	ns	8	16	ns	0.003	ns	4.7	ns	-	-
Block	3	0.12	ns	0.6	ns	3	30	ns	0.001	ns	24.7	***	7.1	Ns

*,**,*** Significant at p≤0.10, p≤0.05, and p≤0.01, respectively; ns = not significant

[†] Mean squares for GPC, NHI and NUE_f only pertain to hard red winter varieties

[‡] Degrees of freedom for Tot. N Rate = 6, and Tot. N x V = 12

Table 4.8 (continued)

Lexington 2009

Source of Variation	df	Grain yield		Test weight		df†	GPC		NUE$_f$		FLN		TN‡	
Total N Rate (TN)	4	0.68	***	2.0	ns	4	1286	***	0.027	**	-	-	64.8	***
Variety (V)	3	0.63	**	184.7	***	3	409	***	0.053	***	-	-	22.2	ns
Spring N (SN)	1	0.15	ns	0.1	ns	1	51	ns	0.024	ns	-	-	-	-
TN x V	0.18	0.18	ns	1.5	ns	8	58	ns	0.006	ns	-	-	9.4	ns
TN x SN	0.44	0.44	**	1.1	ns	4	59	ns	0.006	ns	-	-	-	-
V x SN	0.11	0.11	ns	0.2	ns	3	12	ns	0.000	ns	-	-	-	-
TN x SN x V	12	0.26	ns	1.7	ns	8	72	*	0.012	ns	-	-	-	-
Block	1.76	1.76	***	4.0	**	3	310	***	0.018	ns	-	-	17.0	ns
Arlington 2009														
Total N Rate (TN)	4	0.09	**	0.9	ns	4	230	***	0.014	***	-	-	61.4	***
Variety (V)	3	2.37	***	323.7	***	3	354	***	0.057	***	-	-	65.6	***
Spring N (SN)	1	0.05	ns	2.5	ns	1	159	***	0.001	ns	-	-	-	-
TN x V	12	0.02	ns	2.7	*	8	21	ns	0.003	ns	-	-	4.8	ns
TN x SN	4	0.08	**	1.5	ns	4	29	0.1	0.002	ns	-	-	-	-
V x SN	3	0.05	ns	1.6	ns	3	43	**	0.004	ns	-	-	-	-
TN x SN x V	12	0.03	ns	1.8	ns	8	17	ns	0.002	ns	-	-	-	-
Block	3	0.04	ns	3.0	ns	3	1	ns	0.003	ns	-	-	4.5	ns

*,**,*** Significant at $p \leq 0.10$, $p \leq 0.05$, and $p \leq 0.01$, respectively; ns = not significant

† Mean squares for GPC, NHI and NUE$_f$ only pertain to hard red winter varieties

‡ Degrees of freedom for Tot. N Rate = 6, and Tot. N x V = 12

Table 4.9 Means and comparisons of fall and fall plus spring nitrogen treatments for yield (Mg ha^{-1}) and test weight (kg hl^{-1}) grain protein concentration (g Mg^{-1}), flag leaf nitrogen (FLN: g kg^{-1}) and tissue nitrogen concentration at Zadoks growth stage 30 (TN: g kg^{-1}) at Pendleton

Pendleton 2008

Fall N kg ha^{-1}	Spring N kg ha^{-1}	Grain yield		Test weight		GPC[†]		FLN		TN	
0	0	5.60	b*	78.9	ab	94.0	h	32.5	f	51.5	b
56	0	5.97	ab	79.1	a	103.3	g	33.1	f	52.6	ab
56	56	6.37	a	78.6	ab	121.7	e	36.0	e	-	
112	0	6.35	a	78.0	abc	114.7	f	36.3	de	53.1	ab
112	56	6.39	a	77.1	cde	125.4	de	37.4	cde	-	
168	0	6.31	a	77.7	bcd	122.6	e	38.1	bcd	52.2	ab
168	56	6.41	a	76.0	efg	131.8	bc	39.3	abc	-	
225	0	6.38	a	75.6	fgh	129.7	cd	39.5	ab	53.6	a
225	56	6.20	a	76.6	def	133.6	ab	39.1	abc	-	
281	0	6.09	a	74.4	h	136.8	ab	39.5	ab	53.3	a
281	56	6.25	a	74.6	h	137.9	a	40.4	a	-	
337	0	6.32	a	75.0	gh	135.0	ab	40.5	a	53.0	ab
LSD (0.05)		0.44		1.2		5.2		2.0		1.7	
Pendleton 2009											
0	0	5.35	e	80.8	a	104.8	f	37.7	h	38.6	e
56	0	6.21	d	80.8	a	105.4	f	38.3	gh	43.3	d
56	56	6.59	ab	80.8	a	108.4	f	41.0	ef	-	
112	0	6.56	ab	80.4	ab	108.3	f	40.2	fg	46.8	c
112	56	6.54	abc	79.9	bc	115.1	e	42.6	cde	-	
168	0	6.73	a	80.2	b	113.3	e	41.1	def	49.9	b
168	56	6.70	a	79.4	d	119.8	d	43.9	abc	-	
225	0	6.50	abc	79.5	cd	120.0	cd	43.1	bcd	51.4	ab
225	56	6.36	bcd	79.1	d	124.6	ab	44.4	abc	-	
281	0	6.57	ab	79.1	d	123.9	bc	44.1	abc	52.2	a
281	56	6.39	bcd	78.4	e	127.3	ab	45.0	ab	-	
337	0	6.28	cd	78.3	e	128.6	a	45.3	a	50.5	ab
LSD (0.05)		0.28		0.5		4.1		2.0		1.9	

* means followed by same letter not significantly different ($p \leq 0.05$)

[†] Means for GPC, FLN and TN means pertain only to hard red winter varieties

Table 4.10 Means and comparisons of fall and fall plus spring nitrogen treatments for yield (Mg ha^{-1}) and test weight (kg hl^{-1}), grain protein concentration (g Mg^{-1}), flag leaf nitrogen (FLN: g kg^{-1}) and tissue nitrogen concentration at Zadoks growth stage 30 (TN: g kg^{-1}) at Lexington and Arlington

Fall N kg ha^{-1}	Spring N kg ha^{-1}	Grain yield	Test weight	GPC[†]	FLN	TN
Lexington 2007						
0	0	3.32 a*	78.4 a	119.4 g	34.5 d	35.7 d
28	0	3.19 ab	78.4 a	125.9 fg	35.3 cd	39.4 c
28	28	3.12 abc	78.5 a	130.7 ef	35.8 bcd	-
56	0	2.82 cd	77.2 c	136.0 cde	39.1 a	43.5 ab
56	28	2.71 d	77.2 bc	138.9 bcd	37.3 abc	-
84	0	2.87 bcd	78.3 ab	133.1 def	37.7 abc	42.9 b
84	28	2.84 cd	77.2 c	141.4 abc	38.0 abc	-
112	0	2.75 d	76.5 cd	141.4 abc	38.9 a	46.4 a
112	28	2.93 bcd	76.7 cd	145.8 ab	38.4 ab	-
140	0	2.68 d	76.4 cd	147.7 a	39.9 a	-
140	28	2.69 d	75.9 d	145.1 ab	37.9 abc	-
168	0	2.67 d	76.5 cd	139.6 bcd	38.7 a	44.0 ab
LSD (0.05)		0.32	1.1	7.7	2.8	3.3
Lexington 2008						
0	0	2.20 bc	81.6 ef	88.3 h	27.3 de	29.9 e
28	0	2.34 ab	82.1 cd	88.1 h	26.9 e	33.1 d
28	28	2.48 a	82.5 ab	105.3 g	29.2 bcd	-
56	0	2.48 a	82.5 a	106.5 g	29.2 cd	37.0 c
56	28	2.38 ab	82.4 abc	113.3 f	29.7 bc	-
84	0	2.37 ab	82.1 bcd	115.5 ef	30.7 abc	39.8 b
84	28	2.37 ab	81.9 d	119.6 de	30.9 abc	-
112	0	2.26 ab	81.9 de	122.5 cd	31.1 abc	40.4 b
112	28	2.36 ab	81.5 efg	126.0 bc	31.2 ab	-
140	0	2.01 c	81.9 de	127.2 b	30.8 abc	42.7 a
140	28	1.97 c	81.4 fg	133.8 a	31.0 abc	-
168	0	2.27 ab	81.2 g	130.2 ab	32.4 a	42.6 a
LSD (0.05)		0.25	0.4	4.5	2.1	2.2

* Means followed by same letter not significantly different at $p \leq 0.05$

[†] Means for GPC, FLN and TN means pertain only to hard red winter varieties

Table 4.10 (continued)

Fall N kg ha^{-1}	Spring N kg ha^{-1}	Grain yield		Test weight		GPC[†]		FLN	TN	
Lexington 2009										
0	0	2.49	ab*	80.1	a	104.8	e	-	36.8	b
28	0	2.22	bcde	79.5	abc	117.5	c	-	36.3	b
28	28	2.60	a	79.6	ab	110.3	de	-	-	
56	0	2.42	abc	79.2	abcd	117.2	cd	-	36.7	b
56	28	2.20	bcde	79.4	abcd	126.2	b	-	-	
84	0	2.18	bcde	79.1	bcd	126.7	b	-	41.5	a
84	28	2.06	de	78.7	bcd	130.7	ab	-	-	
112	0	2.10	cde	79.3	abcd	131.3	ab	-	40.4	a
112	28	1.92	e	78.6	cd	135.9	a	-	-	
140	0	2.38	abcd	79.0	bcd	133.0	ab	-	41.4	a
140	28	1.97	e	78.5	d	134.6	a	-	-	
168	0	2.06	de	79.0	bcd	137.0	a	-	41.8	a
LSD (0.05)		0.33		0.9		7.0			2.8	
Arlington 2009										
0	0	2.01	a	77.9	ab	115.8	h	-	44.0	d
28	0	1.93	abc	78.0	a	121.4	g	-	45.2	d
28	28	1.94	abc	77.6	abc	121.8	fg	-	-	
56	0	1.88	bc	76.8	c	124.6	ef	-	47.4	c
56	28	2.01	ab	77.7	abc	123.0	fg	-	-	
84	0	1.85	c	77.3	abc	128.6	bcd	-	48.1	bc
84	28	1.85	c	77.0	bc	127.3	cde	-	-	
112	0	1.92	abc	77.6	abc	126.6	de	-	48.7	bc
112	28	1.81	c	77.5	abc	130.6	ab	-	-	
140	0	1.81	c	77.1	abc	131.6	ab	-	49.8	ab
140	28	1.89	abc	77.5	abc	130.4	abc	-	-	
168	0	1.81	c	77.6	abc	132.6	a	-	50.8	a
LSD (0.05)		0.13		0.9		3.2			2.1	

* Means followed by same letter not significantly different ($p \le 0.05$)

[†] Means for GPC, FLN and TN means pertain only to hard red winter varieties