PNW 578

Nitrogen Management for Hard Wheat Protein Enhancement

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Managing nitrogen (N) to produce both high yields and acceptable protein of hard winter or spring wheat, especially in high rainfall and irrigated systems, has been frustrating for Pacific Northwest (PNW) growers and those who serve them in an advisory capacity. A better understanding of the principles of wheat nitrogen utilization, the relationships of protein to yield and available N, and N management for hard wheat should enable fieldmen, consultants, advisers, and growers to produce high yields of hard wheat with acceptable protein more consistently.

Land-grant programs in the Pacific Northwest have conducted considerable research on N management for irrigated wheat protein enhancement. The research answers many questions related to wheat protein enhancement in irrigated PNW production systems.

Land-grant soil scientists in the PNW have written this publication to share information and to relate in-depth the wheat and N management issues related to grain protein enhancement. The focus is on irrigated wheat, but many of the principles will apply to rain-fed wheat as well.

Contents

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Key Points

Wheat N Utilization

- Most of the N used by wheat is taken up before flowering and later moved to the developing kernel during grain fill.
- Photosynthesis that occurs during grain fill largely determines kernel starch contents.
- Conditions that affect plant stored N at flowering or photosynthesis during grain fill appreciably affect grain protein at harvest.

Yield and Protein

- Growing conditions that affect yield have corresponding effects on grain protein.
- Increasing yield from optimal cultural practices or correcting nutrient shortages can reduce protein if no additional N is provided.
- Inclement growing conditions, such as drought and high temperature, which reduce yield, frequently increase grain protein.
- Stressing wheat during late grain fill and sacrificing yield should not be necessary to produce hard wheat with acceptable protein.

Satisfying N Requirements for Yield

- Yield potential is affected mostly by N available during vegetative growth stages.
- Total available N required per bushel to maximize production ranges from less than 2 pounds to more than 3 pounds depending on the production system.
- The more productive the system, the less N required per bushel for maximizing yield.
- Use of soil testing to measure residual N is essential for the most accurate estimates of N requirements to maximize yield.

Nitrogen and Wheat Protein

- Available N is the most critical factor affecting grain protein.
- Increasing available N during vegetative growth increases both yield and protein, except under conditions where available N is extremely deficient or excessive.
- The N required for acceptable protein may exceed that required to maximize yield by 0.4 pound N per bushel.

Late Season N

- Applying all the fertilizer N required in irrigated situations, for both maximum yield and acceptable protein, during vegetative growth can cause excessive vegetative growth and reduce yield.
- Nitrogen applied after vegetative growth is used primarily to increase protein.
- The protein increase from late N depends on the N rate and the wheat plant N content.
- The protein increase from late N is little affected by N sources, wheat variety, or planting dates.
- Late N induced protein increases in most irrigated field trials have led to improved baking quality.
- The economic return from late applied N depends on N fertilization costs, yield, the protein increase, and the protein discount or premium.

Estimating Protein

- Flag leaf N testing can be useful for estimating grain protein and the protein increase from late N.
- Protein may not increase much if flag leaf N concentrations at heading exceed 4.2 to 4.3 percent.

Wheat grain protein is an important quality factor that influences the marketability of all wheat market classes in the United States. High protein is desirable for all hard and durum wheat market classes, and in some soft wheat markets, when soft wheat is used for specific noodle or bread products. Otherwise, lower protein is desired for many soft wheat uses. Higher protein is associated with increased kernel hardness, gluten strength, and loaf volume.

Hard wheat with higher protein frequently is marketed at a premium compared to lower protein wheat of the same market class. When high protein wheat is limited in supply, the high protein premium may represent as much as 50 percent or more of the market price in low price years. When expected hard wheat prices or high protein premiums appreciably exceed soft wheat prices, some producers shift their soft wheat acreage to hard wheat classes.

While some rain-fed production areas, such as the Northern Plains, have climates that allow the routine production of high protein hard wheat or durum classes, other rain-fed areas produce high protein wheat less frequently depending on available moisture, temperature, and greater fluctuations in yields. Given highly productive wheat in high rainfall or irrigated systems, low protein levels are the general rule unless growers make a determined effort to effectively manage available nitrogen resources for high protein. Even then, intensive N management involving higher N or late season N applications can fail to produce the desired result of high grain protein.

LEGEND:

HRS = hard red spring wheat
HRW = hard red winter wheat
SW = soft white wheat
SWS = soft white spring wheat
SWW = soft white winter wheat
VPR = volume to protein ratio

Failure to consistently produce high protein wheat despite greater expenditures of resources is frustrating for hard wheat growers throughout the western U.S. The situation is exacerbated under some irrigation systems. In a 1999 survey in western Idaho, hard red spring wheat (HRS) from furrow irrigated fields averaged 2.2 percent lower protein than wheat from sprinkler irrigated fields (11.1 vs. 13.3 percent), despite 100 pounds N/acre more fertilizer N applied to the furrow irrigated wheat.

Hard wheat market classes differ in the premiums for higher protein and the discounts for less than desirable protein concentrations. The average annual market prices in Portland, OR, for hard red winter (HRW) and HRS wheat at various protein levels since 1982 are shown in Fig. 1a and 1b. The HRS prices and protein premiums or discounts generally exceeded those for HRW wheat.

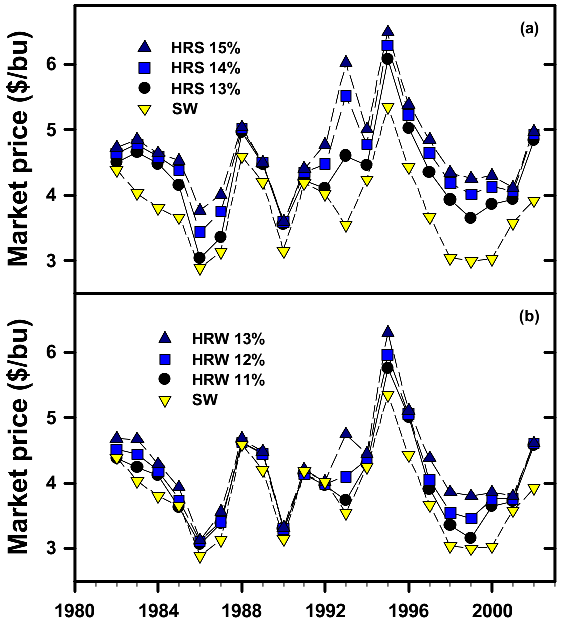
The difference in gross returns for irrigated or high rainfall soft whites and hard reds can be calculated using annual market prices in Portland, OR, for soft whites and hard reds at 13, 14, and 15 percent since 1982. Hard red spring or winter wheat was assumed to be 95 percent as productive as soft white spring or winter wheat. Yields for soft white winter (SWW) of 120 bushels/acre (bu/acre) and soft white spring (SWS) wheat of 96 bu/acre were used for the comparison.

The average difference in gross returns for hard red spring at 13, 14 or 15 percent protein as compared to SWS wheat were $24, $47, and $61 per acre, respectively. Avoiding the discount below 14 percent was more critical than gaining the premium above 14 percent. Discounts per bushel (for protein <14%) can be as much as three times the premium (for protein >14%).

For HRW wheat, the gross return over SWW wheat was only 21 cents/acre for 11 percent protein HRW, $12/acre for 12 percent protein, and $31/acre for 13 percent protein. Historically, the gross return for HRW over SWW wheat is considerably less than the gross return for HRS vs. SWS. Also, the discount for lower protein HRW has been less than the discount for low protein HRS. For the gross return comparisons, additional N application and fertilizer costs were not considered.

Producer interest in HRS fluctuates with the price differential between the soft and hard wheat market classes. There would be greater production of HRS were it not for grower concerns about producing HRS with acceptable protein. Understanding the issues related to wheat protein is critical if producers are to avoid or minimize low protein discounts and maximize their economic returns. This bulletin reviews many factors that govern wheat protein and mentions selected PNW research that addresses

Fig. 1. Average annual wheat prices in Portland, OR, for hard red spring (a) and hard red winter (b) wheat market classes at different protein as compared to common soft white wheat.



questions about the nitrogen management required to produce high yields of wheat with acceptable protein.

Wheat Nitrogen Utilization

All protein consists of amino acids. Nitrogen is critical for protein synthesis as N is part of the basic structure of all amino acids. Without adequate N, amino acids aren't available for protein synthesis.

Providing adequate available N is arguably the most important management factor for producing high protein hard wheat, especially in high rainfall or irrigated production. Variety selection, water management, weed and insect control, and other crop management practices all impact protein in harvested wheat. But failure to understand the importance of N and its proper management for enhancing protein is the single most common reason for low protein discounts and grower disappointment in marketing hard wheat. Effective N management throughout the season plays a critical role in producing high quality, high protein hard wheat.

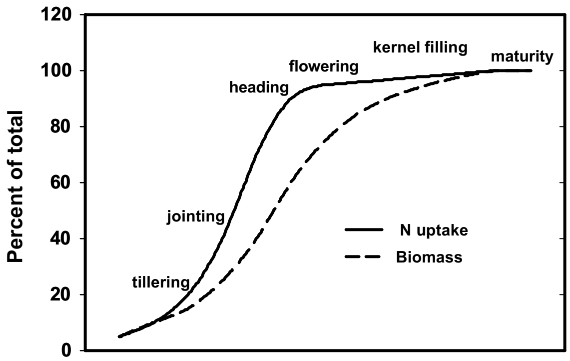
N Uptake

Wheat uptake of soil N depends on the stage of growth, growth rate, and the availability of ammonium (NH_4-N) and nitrate-N (NO_3-N). The N accumulated in the wheat plant during vegetative growth follows a sigmoidal pattern (Fig. 2). Uptake occurs slowly during early stages of plant establishment and tillering, proceeds most rapidly from late tillering through heading, and slows as flowering is completed and kernel filling begins.

The relative uptake and accumulation of N in the wheat plant precedes the production of biomass during vegetative growth (Fig. 2). Maximum daily N uptake per acre by wheat can approach 2 or 3 pounds/day (lb/day) under favorable conditions.

While most N uptake occurs before flowering, some N also can be taken up during the grain filling process. Volatile losses of N from the plant can reduce N available for translocation to the grain. No more N may be found in the plant at maturity than is measured at flowering.

Fig. 2. Percent of total biomass and N uptake during the season in relation to growth stages.



The N accumulated by the plant through early and mid vegetative growth stages is used primarily for increasing yield potential. Available N initially increases wheat yield by increasing the number of seed bearing tillers per unit area, which is typically the greatest single yield component affecting grain yield. Yield also is increased by increasing the potential number of seeds per tiller, but the effect is generally secondary to the tiller number.

Nitrogen uptake during and after heading (emergence of the spike from the flag leaf sheath) is used less effectively for increasing yield because by then, number of tillers and seeds per tiller are set and yield potential has largely been determined. Late season available N can marginally influence yield under N limited conditions by increasing individual kernel size. However, increased kernel weight compensates little for reduced tillering or seed numbers. Late season available N influences grain N content and protein to a greater extent than yield.

As vegetative growth is completed with the full extension of the stem, the plant switches from using its energy and nutrient reserves for vegetative growth or maintenance of stem and leaf biomass to kernel development. Nutrients, including N and soluble carbohydrates, are translocated from older plant tissues (stems, leaves, awns) to the developing kernels where they are used to support cell division and expansion, and the synthesis of storage proteins and starch. As older leaf tissues are depleted of their nutrient and carbohydrate reserves they senesce.

The N reserves in the plant at flowering may constitute all that is required for maximizing yield, and most of this N is translocated to the developing grain. In contrast, carbohydrates in the plant at flowering represent typically much less than half the total carbohydrate used for the developing grain, as grain filling depends more on carbohydrates produced from photosynthesis after flowering.

Drought, or reduced access to moisture from rain or irrigation, may slow the translocation of carbohydrates and nutrients to developing kernels, but the plant is remarkably efficient in this translocation even with moisture stress. However, drought or high temperatures after flowering reduce photosynthesis and the availability of new photosynthates or carbohydrates available for filling the grain. Late season moisture stress tends to reduce starch accumulation more than protein accumulation in the developing kernel. Grain protein concentration at harvest largely depends on the relative amounts of kernel N and carbohydrate that accumulate during grain fill.

There is some indication that N can be lost from wheat plants by volatilization from the above-ground biomass. It is not unusual in research studies to measure less N in the plant at maturity than was measured in the plant at flowering. Volatile N losses and all the factors responsible for it are not well understood. Volatilization generally occurs when excess N is available to the plant. Volatile losses of N may reduce plant N otherwise available for protein synthesis in the developing kernel.

Yield and Protein Relationships

The inverse relation of yield and grain protein concentration is well known in rain-fed production systems. In low rainfall systems N is applied in limited amounts, if at all, to avoid excessive vegetative growth that can deplete limited soil moisture before flowering and grain filling. The N is applied to match long term average production, yet production may fluctuate considerably from year to year depending on available moisture. As available moisture increases during grain fill, yield increases from larger and better filled kernels that are higher in starch and lower in protein concentration. This dynamic accounts for much of the fluctuation in grain protein from one year to the next in all production systems, but especially rain-fed systems.

The same phenomena occurs in higher rainfall or irrigated production systems, though yield and protein may not fluctuate annually as widely as in low rainfall systems. The change in protein with change in yield actually depends on the available N. A case study involving irrigated HRS production in central Oregon provides examples of protein both increasing and decreasing with higher yield (Fig. 3).

At first glance there appears to be no relation between protein and irrigated yield (Fig. 3a). Partitioning the yield data into sites that are less than and over 12.5 percent protein shows two distinct response curves (Fig. 3b). Protein increased as yield increased for all sites where protein was less than 12.5 percent, suggesting that available N at these sites was not adequate for maximizing yield. In contrast, protein declined as yield increased at sites where protein exceeded 12.5 percent, suggesting N was adequate for maximizing yield, higher yields were occurring for reasons unrelated to available N, and higher yields were diluting grain protein.

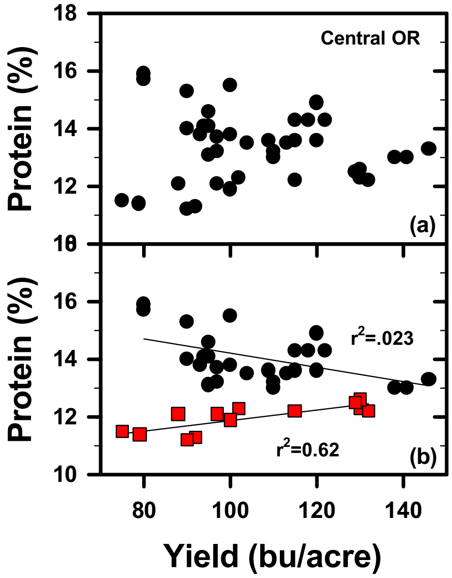


Fig. 3. (a) The relation of irrigated HRS protein to yield in central Oregon. The relations in (b) represent the linear best fitted lines for sites with protein [<12.5% (squares) and >12.5% (circles)].

Average temperatures during grain fill often fluctuate annually as much in irrigated as in rain-fed systems, and probably account for much of the annual yield and protein fluctuation in an irrigated wheat region. Beyond the affects of temperatures during grain fill, yield and protein fluctuate in irrigated systems in response to several crop management practices or soil conditions.

Theoretically, any cultural practice that markedly affects yield also can affect protein at harvest. Higher yields due to factors other than available N or moisture (e.g., soil productivity, more optimum planting dates, variety selection, and alleviating other nutrient shortages) can reduce grain protein. It occurs when either the number of kernels is increased relative to the plant N reserves or individual kernel size is increased from better grain filling and greater starch content (protein dilution). In either case the result is the same—lower grain protein concentrations.

The effect of nutrients other than N is a case in point. When biomass increases and yield is markedly enhanced from applying nutrients such as phosphorus (P), higher grain yields can result in lower grain protein (Fig. 4). Even N, applied in limited amounts under extremely deficient N conditions, can result in lower grain protein concentrations when yield potential is appreciably increased, as described in more detail below.

Producers frequently ask whether sulfur (S) is needed to enhance grain protein. Sulfur apparently is more limiting for yield than for protein. Providing adequate S earlier in the season for yield should not limit the protein increase from late season N. In some cases, preplant applied S without additional N can cause sufficient yield increase that grain protein is actually reduced (Fig. 5). Few published studies have addressed the need for N combined with S in late season applications.

A common grower and fieldmen misconception is that moisture stress during late grain filling is necessary to increase protein to acceptable levels. In three of four seasons at Parma, ID, protein increased when yield was limited by moisture stress after flowering. But 14 percent pro-

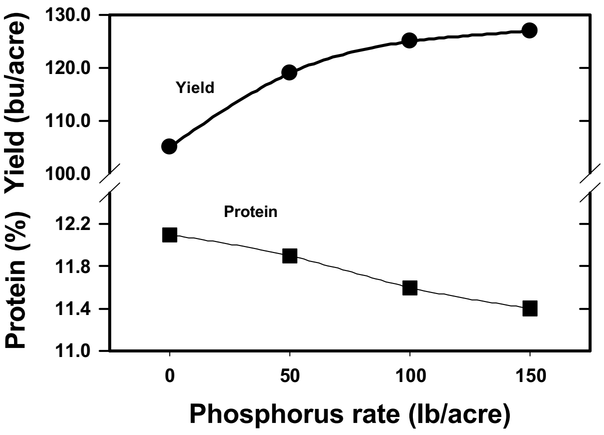
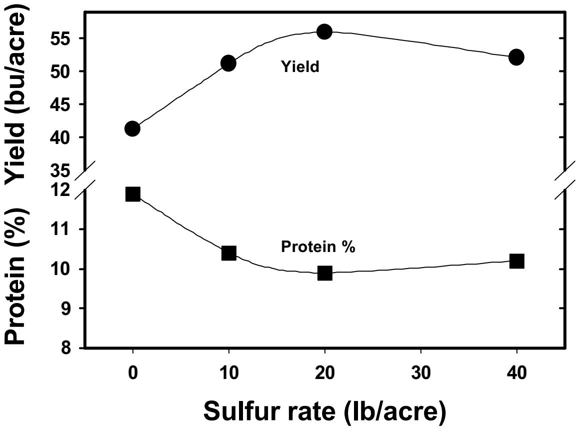


Fig. 4. Irrigated winter wheat yield and protein as affected by different phosphorus (P) rates applied previously to the site.

Fig. 5. Rain-fed winter wheat yield and protein response to increasing sulfur (S) rate.



tein was gained without inducing the stress (and sacrificing yield) if adequate late season N was effectively incorporated at heading. Similar results were obtained in Aberdeen, ID, studies. Therefore, it should not be necessary to sacrifice yield for the sake of getting acceptable protein.

Some growers have asked if excessive late season moisture, especially as rainfall or sprinkler irrigation, can reduce protein at harvest. In southern Idaho studies, protein was unaffected by watering with sprinklers later than necessary for maximizing yield, but blackpoint or fungal discoloration of the germ end of the kernel increased.

Satisfying the N Requirements for Yield

Failure to reach acceptable protein for hard wheat is commonly due to underestimating the amount of N necessary for satisfying the N required for yield. The N required to maximize yield depends largely on the production system. In dryland systems as much as 3.3 pounds of available N/bu was necessary to maximize production. In contrast, well managed irrigated wheat may require as little as 1.6 to 1.8 pounds of available N for each bushel. Typically, the more productive the system (the fewer the limitations to yield), the greater the N use efficiency, and the less N required per bushel to maximize yield.

Still, the high yield potential of currently available varieties requires that sufficient N be available. Total available N includes primarily residual soil N, mineralized N, and applied fertilizer N. Many producers may not be accustomed to providing as much N as is needed for irrigated wheat production, especially if the wheat is considered a rotation crop and not managed intensively.

Wheat protein surveys suggest that roughly a third of the soft white wheat in southwestern Idaho is under-fertilized with N, and about the same fraction is over-fertilized. This comes as little surprise given the relatively low percentage of soil testing done for irrigated wheat in the region. Without knowing the residual N available, it's difficult to know how much to apply to satisfy the N required for yield, much less the N required for raising protein to acceptable levels. Effective N management starts with a representative soil sample and the measurement of residual N available for the crop. All PNW states have guides for estimating wheat N requirements for yield.

Fertilization practices that increase the effectiveness of applied N also will serve to maximize protein in the grain. Late winter or early spring top-dressed N on irrigated hard red winter (HRW) wheat increased protein more than preplant fall applied N in all three years of study (Fig. 6). Avoiding excessive irrigation and leaching of N beyond root systems also can increase N use efficiency, yield, and protein. In rain-fed systems the effectiveness of timing can differ.

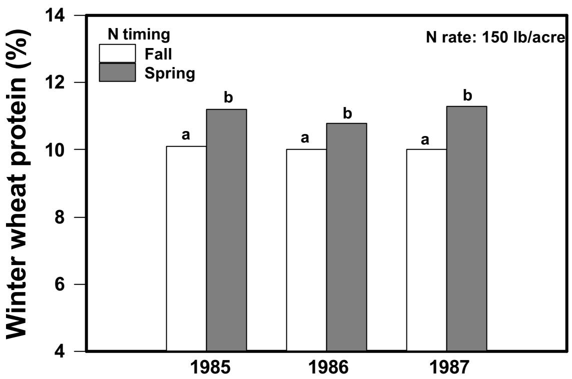
Nitrogen and Wheat Protein

Low wheat protein can be attributed to insufficient available N to satisfy the N required for both yield and acceptable protein for the season's growing conditions. Other factors such as low protein wheat varieties, or higher yields from more favorable conditions, may exacerbate the N deficiency; but inadequate N is fundamentally the issue for low protein.

Wheat protein at harvest can be both increased or decreased with increased available N during vegetative growth, depending on the severity of the N deficiency (Fig. 7). The first increment of N may reduce grain protein when N is severely deficient. When severely N deficient, wheat responds initially to increased available N by increasing seed number (by increasing seed bearing tillers and the number of seeds per head), more so than increasing seed size. Although total grain protein N harvested per acre increases, the grain protein concentration of individual kernels is reduced. Note in Fig. 7 that it took about 130 pounds fertilizer N/acre to match the protein in the untreated wheat.

Under most field conditions N is not severely deficient, and additional available N (as with greater applied N) simultaneously increases both yield and protein. Higher yield and protein, for hard wheat classes in particular, generally ensure higher returns to applied fertilizer N, as there

Fig. 6. Winter wheat protein as affected by pre-plant fall incorporated and late winter-early spring top-dressed urea N. Parma, 1985-87.



is more grain to market and at higher prices. However, if only enough N is available for maximizing yield, grain protein is likely too low for avoiding low protein discounts.

As Fig. 7 suggests, producers maximizing yield with the optimum available N may increase protein from less than 11 to 12.5 percent, but protein is still short of the 14 percent protein necessary for marketing HRS without price discounts. In Fig. 7, another 60 pounds of N/acre above that required for yield was needed to raise protein to the desired 14 percent level.

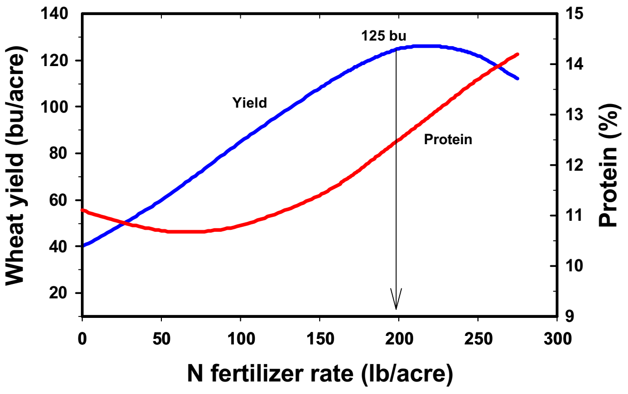
Only when most of the N required for yield is supplied will further N additions raise protein in the developing grain. At this point, the protein increase is often directly related to the amount of N available. This linear phase of protein increase with additional N continues well beyond the point where yield is maximized and generally to protein levels of 14 percent in HRS. Above 14 percent, the protein increase with additional N is sometimes reduced to the point where it may not be measurable, economically significant, and can be counter productive.

Varieties are commonly grown for their yield potential. Varieties can differ in protein content even though they are grown under the same conditions and may yield the same. Equally or more productive but lower protein varieties are more difficult to produce with acceptable protein because it typically takes more available N.

Maximum yield is associated with about 12.5 percent protein in HRS, about 11.5 percent in HRW, HWS, and durum wheat, and 10.5 percent in SW wheat. Protein concentrations beyond these levels may be associated with improved hard wheat quality, but they generally are not necessary for maximizing yield. Acceptable hard wheat protein may be 1.0 to 1.5 percent higher protein than is associated with maximum yield. In some cases protein concentrations well above the minimum required for yield may be associated with reduced yields.

Producers accustomed to fertilizing primarily for yield may not appreciate the extra N required for maximizing production of wheat with acceptable protein. Independent irrigated grower field surveys in central Oregon and southwestern Idaho in 1999 found the average amount of applied fertilizer N associated with 14 percent protein HRS to be 2.2 to 2.3 pounds per bushel. Research and case studies in irrigated HRS indicate the total available N (including applied fertilizer, residual, and mineralized N) required to produce grain with acceptable protein (14 percent) may be upwards of 2.8 to 3.2 pounds N per bushel, or considerably higher than the 1.6 to 2.0 pounds N/bu required for simply maximizing yield.

Fig. 7. The response of irrigated wheat yield and protein to increasing fertilizer N in a central Oregon study.



The additional total available N required for maximizing the production of hard wheat with acceptable protein as compared to that required simply to maximize production can be calculated. Using the above survey, case study information, and related research, the additional fertilizer N requirement for reaching acceptable protein is 0.4 pound N/bu (2.2 pounds N/acre for acceptable protein; 1.8 pounds N/bu for maximizing yield) higher than that required for maximizing yield. It translates into 40 pounds additional N/acre for a production level of 100 bu/acre.

Late Season N for Increasing Protein

Applying N between the boot and flowering growth stages is a common practice for increasing irrigated HRS or HRW protein. Even later applications are made in some cases. Research shows that N applied in split applications with the last application at boot or later growth stages often causes higher protein in irrigated HRS. Sufficient N must be applied early to support adequate early growth and development to support maximum economic yields. However, if all the N required for both yield and protein enhancement is applied at seeding there is risk of excessive vegetative growth, lodging, reduced yields, and lower quality. The response of wheat to late season N in low rainfall production systems may differ substantially from irrigated or high rainfall systems.

Ideally, only the N required for protein enhancement should be applied at boot stage or later. If late season N increases yield, the protein is likely to be well below the 14 percent target. Protein levels of 13 percent or less after late season applied N suggests either that the late season N was ineffectively used by the plant or that more late season N was required than was applied. Several factors can influence the protein response to late season N, descriptions of which follow.

Rate and Timing

An obvious factor governing the protein increase from late season N is the rate used. The protein increase from late season applied N is generally directly related to the rate applied, at least for protein raised to 14 percent. Increasing protein beyond 14 percent with applied N can be more difficult as protein may increase proportionately less with each unit of N applied.

There may be an upper limit to how much late season N can be applied in one application in order to increase protein. As much as 75 pounds late season N/acre applied as urea increased lodging and reduced yield in some years of a southwestern Idaho irrigated wheat study.

The timing of late season applied N affected the protein increase in some studies but not others. Late season N is applied commercially from the boot stage through grain filling. Most of the late season N is applied from boot to flowering growth stages. When protein differences occur from N applied during this period, protein is generally higher from flowering stage applied N than N applied at boot or heading stages.

The effectiveness of the timing for protein enhancement depends to some extent on whether the applied N is used for increasing yield. Yield is more easily affected by boot stage applications than at flowering or later growth stages. Consequently, when yield is limited by N, late N applied at the boot and heading stages may result in lower protein than when applied later. Protein concentrations increase from late season N applied as late as the milk stage.

Yield Effects

Ultimate yield can appreciably affect the effectiveness of late season N applied for protein enhancement. For example, total protein N for 12 and 14 percent protein with 40 bu/acre wheat differs only about 7.5 pounds/acre, but 22.5 pounds protein N/acre for 120 bushel wheat (Fig. 8). A given amount of late season N can't be expected to increase the protein percentage by the same amount in both 40 and 120 bushel wheat. From this illustration, and assuming all the applied N goes to increasing protein, a given amount of applied N, say 40 pounds N/acre, would be three times more effective increasing protein in 40 bushel wheat as compared to 120 bushel wheat.

Fig. 8. Protein N content of wheat on a per acre basis as affected by yield and protein percentage. The number near the end and below each line is the difference in protein N as protein increases from 13 to 15 percent.

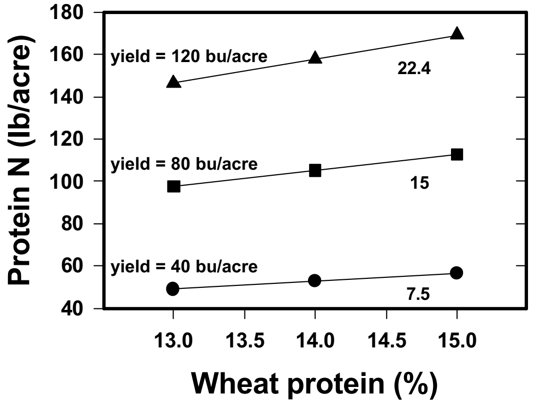
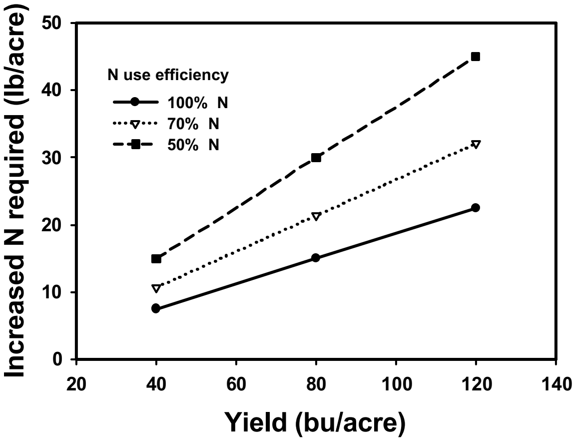


Fig. 9. The N required to increase grain protein from 12 to 14 percent for different yield levels as affected by different N use efficiencies (additional grain protein N as a percent of N applied).



From a different perspective, three times more N is required to change protein a percentage point for 120 bushel wheat than for 40 bushel wheat. Failure to reach 14 percent protein in HRS can result from too little N applied for the yield involved.

The protein N in 40 bushel wheat at 13 percent protein is about 50 pounds N/acre, but is 150 pounds/acre for 120 bushel wheat. The amount of protein N per acre increases as the protein increases, but total protein N per acre is much more sensitive to yield than it is to changes in the protein percentage. The higher the yield, the more N required to change protein.

N Use Efficiency

Late season applied N is seldom if ever 100 percent effective, that is, used totally for increasing protein. Some may volatilize to the atmosphere, some may be incorporated into soil microbial tissue, or the plant may use it for metabolic functions other than protein synthesis in the grain. The amount of N required to change protein from 12 to 14 percent protein is shown in Fig. 9 for different yields and N use efficiencies. Note that for all the N efficiency lines plotted in the figure, the N required to change the protein percentage increases as yield increases, but the lines are not parallel, because at lower efficiency more N is required to cause the same protein change.

Application and Irrigation Method

The efficiency by which late season N is used for protein enhancement depends in part on several factors related to the N application itself and the existing and subsequent soil and water conditions. Late season N is most conveniently applied through sprinkler systems. Applying N through the lines reduces application costs, assures adequate and more uniform N incorporation for root uptake, and allows higher N rates to be used than can be used with concentrated foliar sprays.

Sprinkler irrigation provides more flexibility in managing late season N for protein enhancement than any of the alternatives. If the N can't be injected through the lines, it can be applied as a dry N fertilizer by air or with ground equipment and then watered in with sprinkler irrigation, but this entails a separate application and higher cost. Ground equipment can reduce yield in the wheel tracks, but on a field basis yield losses are 1 to 3 percent.

Providing late season N without sprinklers is more of a challenge. Concentrated foliar sprays at heading are as effective as sprinkler applied or incorporated N for increasing protein at harvest. But there is a limit on how much foliar N can be applied without incurring leaf burn. Appreciable burning of the upper leaves of wheat can reduce yield, as these leaves are critical for providing late season photosynthates or starch for the developing seed.

In one three-year study at Parma, ID, yield was reduced 13 percent when a quarter of the flag leaf was burned with a N rate of 45 pounds N/acre applied as urea-ammonium nitrate (solution 32 or uran). Solution 32 typically causes more leaf burn and reduced yield than comparable amounts of soluble urea N applied in the same manner. The two N sources did not differ in the protein that resulted from their foliar application in three years of testing at Parma (Fig. 10). Solution 32 can be applied with drop lines extending into the canopy from booms to reduce the foliar burning of upper leaves, but must be subsequently sprinkler irrigated for maximum effect.

Top-dressed dry N fertilizers with furrow irrigation can be less effective applications as they depend primarily on rainfall to move the N deep enough to be taken up by roots. Rainfall is infrequent, and generally too little in many areas and seasons to adequately incorporate surface applied N in late vegetative and grain filling stages. Also, subsequent furrow irrigation not only fails to adequately incorporate top-dressed N, it may exacerbate volatile losses of surface applied ammonium N fertilizers such as urea.

Dry N applied and then incorporated with basin flood irrigation avoids some of the pitfalls of furrow irrigation because the N is presumably better incorporated with the wetting front uniformly advancing into the soil.

Fertilizer N is sometimes added with the water used for furrow irrigation. Applying N uniformly with any irrigation system is limited by the uniformity of the water application. In furrow or basin irrigation systems, the uniformity of the water application depends largely on the down slope advance time of the water. Water infiltration is greatest nearest the inlet or top of the field.

The uniformity of application is poorest with furrow irrigation, not to mention the poorer watering efficiency. Typically, as much water is lost in the runoff as infiltrates into the soil. To minimize N loss in the runoff, irrigators will often shut off N when the water advance reaches two-thirds to three-fourths of the distance of the furrow length. Uniform N application in furrow irrigation systems is especially challenging.

Fertilizer N can be variable rate applied to areas most in need of supplemental N. However, the technology depends on appropriate mapping of the field variability in predicted protein. Spectral aerial or satellite images may eventually prove to be useful for mapping field wheat N status and guiding variable rate applications.

Planting Dates and Varieties

Planting dates and varieties have significant effects on yield and protein. Earlier plantings are typically more productive and can result in lower grain protein. But planting date research has given mixed results with respect to protein. Effects of planting dates on protein differed in some years, but the response to late season N was unaffected by planting dates in a three year irrigated southwestern Idaho study (Fig. 11). In the same study, varieties differed more consistently in protein than planting dates.

Regardless of their protein differences, varieties of both hard red and hard white spring wheat responded similarly to late season applied N. Protein increased about 0.3 percent for each 20 pounds/acre of N applied at heading regardless of planting date or variety.

Late Season Moisture

As mentioned earlier, some speculate that stressing wheat during late grain fill may be necessary to produce hard wheat with acceptable protein. Although reduced yields from low moisture can increase protein, research suggests that yields, with appropriate N management, need not be sacrificed to produce 14 percent protein HRS wheat. In fact, imposing a moisture stress by withholding water may reduce the effectiveness of previously applied N and reduce protein.

A late season stress imposed by withholding water after flowering had little influence on the protein response to late season N in three of four years of a southwestern Idaho study. However, regardless of the late N rate, in three of four years, there was evidence that protein was lower with less irrigation during grain fill than it was when fully irrigated. Lower protein from low moisture conditions likely resulted from several factors including more shallow incorporation of previously applied N, limited root activity where N was positioned, and reduced N

Fig. 10. Protein of Ute hard red winter wheat as affected by foliar applied urea or uran solutions in three years of study at Parma, ID.

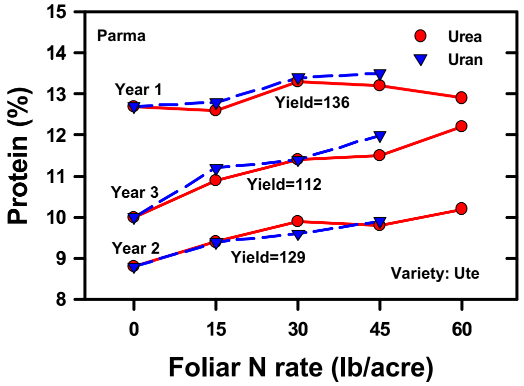
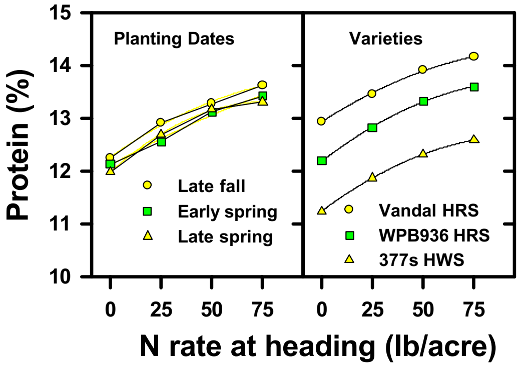


Fig. 11. Protein response to late season N rates as affected by planting dates and varieties of hard red or hard white spring wheat over three years at Parma, ID.



mineralization. Maintaining adequate soil moisture during grain fill is important for wheat roots to access soil N for protein enhancement.

Economics

The economic return from late season applied N depends on the cost of the additional N and application, the resulting yield, the protein increase, and the protein discount or premium when the wheat is sold. The cost of fertilizer N will vary depending on year and region and is greatly influenced by energy prices.

Fertilizer N costs for the rate of 40 pounds N/acre would range from $11.20 to $14.40 per acre if fertilizer costs ranged from 28 to 36 cents per pound of N. Of the variables affecting economic returns, fertilizer costs are probably the least variable. The return from late season applied N must at least cover the costs of the additional N, as well as any application costs.

The yield is best estimated based on historical averages for the field, then adjusted for the current season growing conditions. Unfortunately, yield is difficult to predict with accuracy before flowering, when late season N decisions are typically made, because of the uncertainty of conditions during grain fill.

Irrigated wheat yields are easier to predict than rain-fed wheat yields, and rain-fed wheat yields are better predicted with knowledge of the available soil moisture at flowering. Irrigated yields are typically less variable than the protein increase or low protein discount.

The protein increase with late season N is quite variable. In 10 Montana research trials over two years, late season N at heading (40 pounds N/acre) was applied to irrigated HRS wheat adequately fertilized preplant for yield. The protein increase ranged from 0.5 to 2.0 percent for grain yields ranging from 57 to 101 bu/acre. Where protein was between 13 and 14 percent without the late season N, the additional N in four of five sites increased protein to at least 14 percent.

Similar research in southern Idaho over six seasons at the same location indicated protein percentage increases ranging from 0.4 to 1.5 percent with similar late season N rates applied to irrigated HRS wheat adequately fertilized previously for yield. From these studies, it's clear that the effectiveness of late season N for protein enhancement can range widely. This range in effectiveness or N use efficiency makes it difficult to accurately predict in a given season the amount of late season N required for 14 percent protein.

The discount for 13 percent protein HRS (relative to 14 percent) in Portland, OR, since 1982 ranged from a low of 2 cents in 1990 to as much as 92 cents in 1993. If you exclude the 1993 year when the discount was abnormally high, the average discount at 13 percent for the period 1992-2002 was 26 cents a bushel. By comparison, the premium for 15 percent over 14 percent protein was 18 cents a bushel for the same years.

PNW growers have no control over the low protein discount. It is difficult to know what the premium will be at harvest, as it depends primarily on the quality (protein level) of carryover stocks and new crop wheat. The quality of carryover stocks is generally reflected in the discount or premium offered since the previous harvest. New crop quality determinations are more difficult to predict, but generally conditions favoring higher yields in major hard wheat production regions (the Great Plains) are associated with lower protein and poorer quality, a demand for higher protein, and greater discounts.

The increase in gross return from late season N is shown in Fig. 12 for various yields, protein discounts/premiums, and changes in protein percentage with late season N. A reference line also is included for costs of additional N at 32 cents a pound for 40 pounds of N (application costs are not represented).

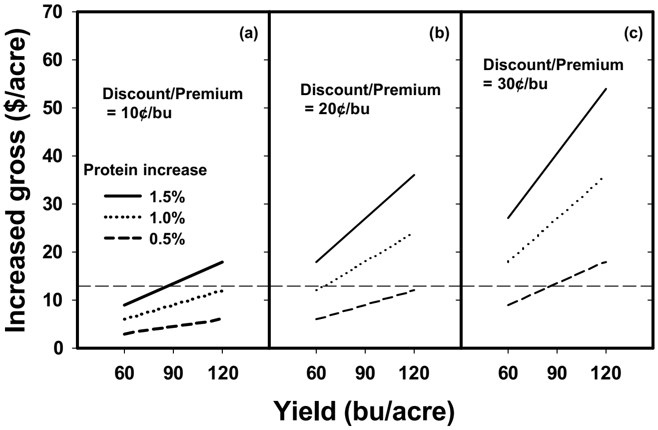
Exceeding N costs was difficult for low discounts/premiums (Fig. 12a). Of the three variables shown to affect the increased gross (yield, protein increase, and discount), yield is probably the least variable. The uncertainty of the protein increase and the low protein discount make it especially difficult to determine the economic feasibility of applying late season N.

Deep Soil N and N Mineralization

Wheat protein can increase whenever additional N, regardless of source, is available to the plant during grain filling. In addition to applied fertilizer N, other sources include residual N available at deeper soil depths, or N mineralized within the root zone, or N in the irrigation water. All these N sources will promote higher grain protein at harvest.

Harvest wheat protein in rain-fed Washington studies was directly related to available N located deeper in the profile. In this study, higher protein resulted from fall-applied N rather than spring-applied N because more of the applied N was moved deeper in the profile with winter precipitation, and root activity during grain fill was greatest at the lower depths where soil moisture was highest.

Fig. 12. The increased gross returns per acre from 40 pounds of late season N as affected by yield, the increase in protein, and the discount/premium.



Soils depleted of moisture have little root activity, and N positioned in dry soils for all practical purposes is unavailable to the plant. Soil moisture during grain filling in PNW rain-fed systems is typically depleted near the surface where most roots are located. Similar results also might be expected in irrigated systems when short water supplies preclude irrigation during grain fill.

The influence on protein of mineralized N during grain filling is largely ignored. Large confined animal feeding operations are providing more manures to sites used for crop production, including wheat. Appreciable manuring can be expected to increase N mineralization. Mineralization of N in manured fields can conceivably provide significant N during the last two months of wheat growth that could be used effectively for increasing wheat protein at harvest.

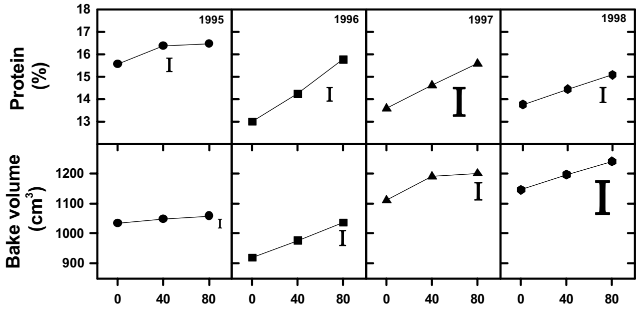
Early cutoff of irrigation during grain fill can limit N mineralization in soil due to sub-optimum soil moisture conditions for supporting biological activity and N release from the organic N pool. Early cutoff can occur in water short years when irrigation supplies are limited, or as a management option used to enhance protein at the expense of yield, although sacrificing yield for acceptable protein should not be necessary with effective N management, as suggested earlier. Early cutoff also can affect the depth of N incorporation into soil and its availability when soils dry in the surface one or two feet, where most of the root system is located.

Baking Quality

Some have questioned whether the protein increase from late season N actually improves bread baking quality. Results from several southern Idaho studies consistently indicate that protein increased to 14 percent or more from early or late season N results in improved baking quality as evidenced by larger loaf volumes (Fig. 13). The only occasion when increasing protein with late N did not improve bread making quality was when protein was already high (at or above 15 percent protein). There is good reason why the HRS market provides better compensation for wheat with protein above 14 percent.

Weather conditions during grain fill have enormous influence on baking quality and can override effects of available N and grain protein. Note that bake volume in Fig. 13 differed among the years, with bake volume higher in the last two years despite protein considerably lower than in the first year.

Fig. 13. Late season N effects on grain protein and loaf bake volume in four years at Parma, ID (1995-98). Bars within each figure represent the LSD at the 10% probability level.



While increased available N and higher protein typically improves breadmaking quality when protein is increased to 14 percent, the improvement in baking quality is not always commensurate with the protein increase at higher protein levels and under some extreme conditions. One measure of protein quality is the loaf volume to protein ratio (VPR). The VPR for any given season was fairly consistent over a moderate range of late season N and moisture conditions in southern Idaho studies at Parma and Aberdeen. Applying as much as 80 pounds late season N/acre reduced the ratio only slightly at Parma in each of four years, but the ratio decreased considerably more when extreme moisture stress occurred from withholding water after flowering. The VPR in these studies was only sensitive to the most extreme variations in available N and moisture.

Apparently there are some conditions where late season N increases protein to 14 percent without a corresponding improvement in baking quality. In a two-year western Oregon study, higher available N applied after tillering consistently increased protein and baking quality. Reserving 40 pounds N/acre of the total N applied for application at flowering did not affect yield, protein, or baking quality in the first year, but reduced yield in the second year, suggesting that available N was limiting yield potential during vegetative growth. Under these conditions protein increased in the second year with late N but without improving baking quality as indicated by loaf volume.

It is not clear why baking quality improves with late season N enhanced protein under some conditions but not others. Nitrogen timing also can affect the relationship between protein content and milling yield of wheat.

Predicting Protein for Protein Enhancement

The protein increase from late applied N depends largely on the N content of the plant at the time of the application, yield potential, and subsequent growing conditions. The final protein in the grain is largely a function of the N in the plant that can be translocated to the developing grain from the non-grain biomass.

Assessment of wheat plant N status has been a focus of several research programs in the PNW. There are likely several means to provide reasonable estimates of the wheat N status. Evidence from some studies follow.

Plant Analysis

Plant analysis has long been used to indicate in-season N needs of PNW row crops. Plant analysis also can be used to indicate in-season N requirements for hard wheat. Lower stem nitrates were used during tillering, and whole plant N at tillering also was used. Several wheat tissues at various growth stages were evaluated for estimating protein in the grain at harvest in southern Idaho.

Flag leaf total N (flag leaf is the last to emerge and is the upper most leaf of the stem at heading) at heading or flowering was more closely related to grain protein at harvest than N in tissues collected at earlier growth stages. Most of the N to be taken up by wheat is in the plant by flag leaf emergence. Flag leaf total N is directly related to the total N in the biomass.

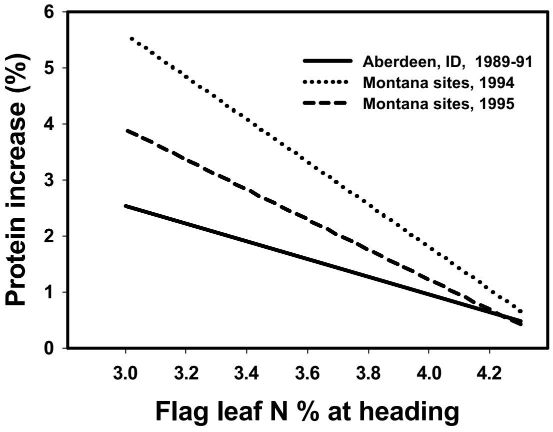
Flag leaf total N concentrations of 4.2 to 4.3 percent at heading were associated with nearly 14 percent protein in irrigated HRS wheat in Aberdeen, ID, studies conducted for three years with two varieties. Similar results were found at several sites across Montana in a two-year study. The relation of flag leaf N at heading and the protein increase in HRS is shown for these two studies in Fig. 14.

In both studies there was little increase in protein with late season N if flag leaf N was at the 4.2 to 4.3 percent concentration. The protein increase from late season N was greater the lower flag leaf total N was below 4.2 percent. In both years of the Montana study, flag leaf N at heading was closely related to the increase in protein with 40 pounds of late N. However, the relation differed in the two years, as the same rate of late N caused a greater protein increase in 1994 than in 1995. Note also that at Aberdeen, ID, during three years the increase in protein with 40 pounds N/acre was lower than it was in Montana.

Clearly, the effectiveness of late season N differs between years and areas, but in all studies the threshold or critical values for a protein increase (4.2 to 4.3 percent N) were fairly consistent. The results suggest that it may be more difficult to predict either the amount of N required to increase protein when flag leaf N values are below the threshold, or the amount of the increase that occurs with a given rate, but the threshold is fairly stable. In that respect, flag leaf N testing is no different from other plant analyses or tissue testing procedures that can determine whether a plant is N deficient, but seldom provide accurate estimates of the rate of N required.

The results from these studies also indicated that 40 pounds/acre of late season N was not adequate for increasing protein to 14 percent when flag leaf N was as low as 3.0 percent. Yield also was limited by low N when flag leaf N was this low. Late season N in excess of 40 pounds/acre may be necessary in some years or regions for gaining 14 percent protein at harvest when flag leaf N at heading is below 3.5 percent.

Fig. 14. Hard red spring wheat protein increase from 40 pounds late season applied N/acre as affected by flag leaf N percentage at heading in different locations or years.



It is critical to collect flag leaves as close to heading as possible, or to carefully document the growth stage of samples collected after full flag leaf emergence. Flag leaf N typically decreases as the plant continues to develop. It may be possible to collect flag leaves before heading and as late as flowering, but the critical flag leaf N values necessary for acceptable protein are higher when sampled before heading and considerably lower when sampled after heading.

Flag leaf N was monitored at flag leaf emergence, heading, and flowering in three southwestern Idaho fields during the 1999 season. In two fields, flag leaf N dropped from 4.62 and 4.24 percent N when flag leaf blades had emerged, to 4.1 and 4.0 percent N at 50 percent head emergence. The change at flowering was even greater, decreasing to 2.5 and 2.3 percent at this stage. The third field received appreciable late season N, and flag leaf N actually increased from flag leaf emergence to heading before declining at flowering. Late season N slows the decline in flag leaf N concentration. Clearly, knowing the growth stage when samples are collected is critical for correct interpretation.

Sampling earlier than heading has the advantage of providing additional time for the analysis to be done and the results related to the grower. It also provides additional time for the N to be applied, especially useful if it takes several days to apply late season N through the sprinklers with several different sets. Unfortunately, flag leaf N levels associated with 14 percent protein are less well documented when flag leaves have just fully emerged than when sampled at heading.

From the limited sampling done to date it appears that critical flag leaf N will be 0.2 to 0.5 percent total N higher at flag leaf emergence than at heading. In any case, if flag leaf N at the early sampling is no greater than 4.2 percent, which is the critical level for the heading stage, additional N should be considered since the concentration is not likely to increase or remain the same at heading without additional N applied.

Flag leaf N seems to work well in controlled research studies where collecting representative samples of both the leaves and grain is relatively easy given the small scale on which the trials are conducted. Successful use of flag leaf N in grower fields to predict harvest protein and supplemental N needs will depend on the care to which representative samples are collected. This is no mean accomplishment given the wide variation in available N, soils, wheat plant N, and yields within fields.

Flag leaf N is only an index of plant N status at specific growth stages. Subsequent conditions during grain filling (higher temperatures, drought stress) will ultimately dictate harvest wheat protein.

Chlorophyll Meter

Non-destructive, in-field plant testing also was proposed for predicting late season N requirements for enhancing protein. Hand held chlorophyll meters were evaluated for predicting the N required for both yield and protein. Relative meter values are obtained by dividing the meter value from one area in a field to meter values in an adequately fertilized area of a field.

The relative values are more useful than the actual values in predicting the need for additional N because chlorophyll meter values (SPAD readings) may differ for different varieties or growth stages. Relative values do, however, require a well fertilized reference area for each field. This technology has potential for providing convenient in-the-field estimates of the need for additional N.

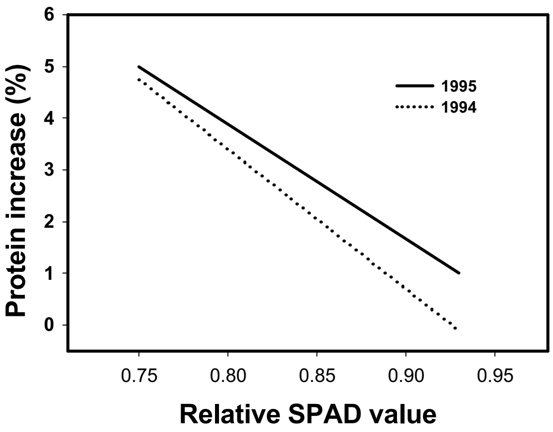
In Montana, relative chlorophyll meter readings (normalized SPAD readings) were closely and directly related to flag leaf N and protein. Similar to flag leaf N, the higher the relative value the less increase in protein that occurred with late season N (Fig. 15). Relative values decreasing from the range of 0.93 to 0.95 indicate a potential for greater increases in protein with late season N.

Spectral Assessment

Spectral reflectance technology using either satellite imagery or digitized images from aerial photographs also has been evaluated for predicting protein at harvest. Reflectance of specific wavelengths of near infrared and red light recorded from aerial filming were closely related to initial N rates, flag leaf N, HRS protein, and the response to late season N in a Montana study. Spectral reflectance is used to create a vegetation index, or NDVI, that is directly related to wheat plant N content when N is primarily responsible for vegetation growth differences.

Spectral assessment has some advantage over in-the-field sampling using either flag leaves or chlorophyll meters. The technology involves rapid data acquisition, and greater resolution of spatial differences in the field that facilitates mapping and subsequent variable rate N applications for enhancing grain protein.

Fig. 15. Protein increase from 40 pounds late season N per acre as affected by relative SPAD value in Montana studies in two different years.



Summary

HRS market prices, frequently higher than SW prices, has stimulated interest among traditional SW wheat producers in this alternative market class. Successful hard wheat production and marketing depends on avoiding low protein discounts. Effective N management throughout the season is essential for assuring both adequate production and acceptable protein. Applying sufficient N for maximizing yield is likely not sufficient for avoiding low protein discounts. Understanding the relationship of protein to yield and available N can be useful for managing N for hard wheat with acceptable protein. Imposing late season moisture stress can reduce yield and should not be necessary for producing wheat with acceptable protein if effective late season N management is used.

Late season N in particular may be necessary for many irrigated producers to avoid low protein discounts, and probably less critical for low rainfall rain-fed production systems. Increased protein from late season N usually improves bread baking quality. The protein increase with late season N can vary appreciably from year to year and location, and depends on many factors: rate and timing, yield potential, application method, irrigation system, and the plant N status, to name a few. The economic returns to late season N are difficult to project because of variable discounts or premiums when the wheat is marketed and the uncertainty of the magnitude of the protein increase with late N.

Effective N management for wheat protein enhancement depends on:

- Satisfying the N requirement for yield with sufficient early season N during vegetative growth.
- Predicting grain protein from estimates of wheat plant N status.
- Satisfying the additional N required for acceptable protein with effective use of sufficient late season N.

Flag leaf total N or chlorophyll meter relative values are useful for predicting whether late season N is required for acceptable protein and for avoiding low protein discounts. The likelihood of a protein response to late season N declines the higher the flag leaf N or the relative SPAD value. Spectral reflectance of infrared and near infrared light using satellite or aerial images have potential for improving yield and protein estimates and facilitating variable rate N applied for protein enhancement.

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