Yield, Protein and Nitrogen Use Efficiency of Spring Wheat: Evaluating Field-Scale Performance

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Abstract

Nitrogen use efficiency (NUE) affects cereal yield-protein relations, N requirements and environmental quality. We assessed field-scale variation in hard red spring wheat (HRS) (*Triticum aestivum* L.) yield-protein relationships and NUE, derived unit N requirements (UNR) for HRS, and evaluated the crop physiologic and environmental suitability of HRS production. Plot-scale studies with tillage and N rate treatments were combined with a field-scale (37 ha) study to evaluate HRS performance. Grain yield, grain N, aboveground plant N, applied N, and pre- and post-harvest root-zone soil N were used to assess components of NUE. Plot-scale data displayed typical yield-protein relations with increasing N supply and a curvilinear, negative relationship between NUE and grain protein concentration (GPC). Field application of plot-derived UNR gave highly variable within-field responses of grain yield (1.3 to 3.8 Mg ha^{-1}), GPC (106 to 179 g kg^{-1}) and N uptake efficiency (12 to 48%). We concluded that: (1) UNR and management based on small-scale plot data cannot be extrapolated to field-scale conditions; (2) uniform N applications will not achieve field-scale goals of grain yield, GPC and NUE; (3) significant proportions of the field may not be suitable for HRS production without site-specific N management strategies that improve NUE; (4) NUE components can be used to evaluate grain yield-GPC relations and to diagnose field areas with over or under application of N, poor N utilization or uptake efficiencies, and significant N loss; and (5) devising N requirements and management strategies for HRS should use a combination of plot- and field-scale data.

List of Abbreviations

GPC, grain protein concentration; G_w, grain yield; HRS, hard red spring wheat; MP, moldboard plow-based tillage; N_{av}, available N; N_f, applied N fertilizer; N_g, grain N; N_{lo}, N losses; N_s, N supply; N_t, aboveground crop N; NT, no-tillage; NUE, Nitrogen use efficiency; PNW, Pacific Northwest; SWW, soft white winter wheat; UNR, unit Nitrogen requirement

Introduction

Worldwide, single-season recovery of N in harvested crops is estimated at 33% of applied fertilizer N (Raun and Johnson, 1999). Poor N recovery is a function of N flows to competing pathways such as gaseous N losses, leaching and biological immobilization (Legg and Meisinger, 1982; Ladd and Amoto, 1986; Haynes, 1997) and inefficiencies in crop N uptake and utilization (Moll et al., 1982; Huggins and Pan, 2003). The soundness of cropping systems with inefficient N use is becoming increasingly questioned as the movement of N beyond agroecosystem boundaries contributes to degradation of air

(Mosier et al., 1996; Mummey et al., 1998) and water (Randall et al., 1997; Burkhart and James, 1999; Huggins et al., 2001) at watershed and global scales (Tilman et al., 2001; Diaz and Rosenberg, 2008) and as producers seek to reduce external farm inputs and costs.

Evaluation of new agricultural practices and technologies should include an assessment of major NUE components derived from soil and crop physiological processes and environmental and economic factors (Huggins and Pan, 1993; 2003). Currently, major directions of change in dryland cropping systems of the Pacific Northwest (PNW) are: (1) a shift from intensive tillage to conservation tillage systems including direct-seed and no-tillage; (2) a movement toward more diversified cropping systems including the production of different classes of wheat (i.e. soft white, hard white, soft red and hard red wheat) and a wider array of rotational crops; and (3) greater interest in precision farming technologies including sensors, applicators, crop models and decision support systems. These agricultural developments are not unique to the PNW and reflect larger national and global agricultural trends. Each has the potential to have major impacts on NUE and, collectively, underscore the need for more comprehensive evaluations of agroecosystem NUE.

Traditionally, high yielding soft white wheat with low grain protein concentration (GPC) (70 to 110 g kg^{-1}) has been grown in the PNW (Rao et al., 1993), favored by the inverse relationship often expressed between grain yield and protein (Terman et al., 1969; McNeal et al., 1982; Loffler et al., 1985). Growers have had mixed success, however, in achieving the high yield and high GPC (115 to >140 g kg^{-1}) required to improve the marketability and economic return of hard white and red wheat (Baker et al., 2003). Unrealized grain protein goals have been attributed to: (1) environmental conditions that promote high yield and low grain protein (Rao et al., 1993); (2) poorly defined UNR and N management strategies for achieving targeted grain yield and protein concentrations (Huggins et al., 1989); and (3) spatially heterogeneous field attributes (Bhatti et al., 1991; Pan and Hopkins, 1991; Busacca and Montgomery, 1992) that regulate and promote large variations in wheat yield, protein and NUE (Mulla, 1992; Fiez et al., 1994 and 1995; Yang et al., 1998). Collectively, these observations suggest that: (1) within-field locations may be more or less suited for achieving grain yield and quality goals for various classes of wheat; (2) realizing wheat yield and protein production goals could be advanced through site-specific farming techniques (i.e. wheat class suitability or N management zones); and (3) N management strategies (i.e. insurance applications of N) aimed at obtaining unrealistic wheat performance goals could promote low NUE and contribute to the degradation of surface and/or ground water quality and lower economic returns for producers.

Small plot experiments evaluating crop response to applied N are typically used to derive UNR, explore regionally-applicable N management strategies (Bock, 1984; Pan et al., 1997) and determine economically optimum N levels (Baker et al., 2003). In situations where large within-field variability in crop yield and grain quality occur, this approach may need

to be augmented with whole field studies in order to devise management strategies applicable at field scales. Towards this goal, we explored the utility of NUE components as defined by Huggins and Pan, (2003) to evaluate a combination of small plot and field-scale experiments to: (1) assess field-scale variation in HRS yield-protein relationships and NUE; (2) derive UNR for HRS; and (3) evaluate the crop physiologic and environmental suitability of HRS production.

Materials and Methods

Three field studies were conducted near Pullman, WA (550 mm average annual precipitation) where dryland HRS (*Triticum aestivum* L., cv. 'WB 926R') was grown following wheat. Two studies consisted of plot-scale experiments and were established on Latah (Fine, mixed, superactive, mesic Xeric Argialbolls) silt loam soils in 1987 and on Palouse (Fine-silty, mixed, superactive, mesic Pachic Ultic Haploxerolls) silt loam soils in 1989. The third experiment was field-scale (37 ha) and conducted in 1999 at the Washington State University Cook Agronomy Farm (46° 47' N, 117° 5' W) located five km NE of Pullman, WA. The field study also had silt loam soils developed in loessdeposits with complexes of the Palouse-Thatuna (Fine-silty, mixed, superactive, mesic Oxyaquic Argixerolls)-Naff (Fine-silty, mixed, superactive, mesic Typic Argixerolls) association (USDA Soil Survey of Whitman County, WA, 1980)**.**

Study Design and Establishment

The two plot-scale studies were randomized, factorial, split-plot experimental designs with four replications and have been previously described in Huggins and Pan, 1993 and Baker et al., 2003. Briefly, tillage was the main plot factor with no-tillage (NT) and moldboard plow-based tillage (MP); subplots were a factorial N by S rate experiment. Results of the S treatment are not included in this report. The MP treatment consisted of fall moldboard plowing followed by disking and harrowing in the spring. Surface wheat residues prior to planting NT plots were estimated at 4000 kg ha^{-1}. The HRS was seeded at 85 kg ha^{-1} on 10 April, 1987 and at 95 kg ha^{-1} on 18 April, 1989 with a no-tillage drill equipped with fluted coulters and fertilizer shanks preceding double-disk seed openers. A 30-cm row spacing was used in 1987 and a 20-cm row spacing was used in 1989. Ammonium nitrate was banded 10 cm below the seed at rates of 0, 56, 112, and 168 kg N ha^{-1} in 1987, and at rates of 0, 90, 134, 179 and 224 kg N ha^{-1} in 1989. In addition, 22 kg P ha^{-1} as triple super phosphate were banded with the applied N (N$_f$).

In the field-scale experiment, a global positioning system was used to establish 369 geo-referenced sample points in a non-aligned grid sampling design over a 37-ha field. The study area was no-till planted on 11 May 1999 with a Great Plains[1] no-tillage drill equipped with leading turbo coulters and low-pressure injection system for banding liquid fertilizer below the seed, followed by double-disk seed openers with 25-cm row spacing. The HRS seeding rate was 112 kg ha^{-1}. Fertilizer was band-applied with the drill during planting at

rates of 162 kg N ha^{-1}, 22 kg P ha^{-1} and 34 kg S ha^{-1} as a solution of aqua ammonia, ammonium polyphosphate and ammonium thiosulfate. Nitrogen fertilizer rates were based on UNR derived from the first two plot-scale studies, a HRS yield goal of 3.3 Mg ha^{-1}, a grain protein goal of 140 g kg^{-1}, and soil inorganic N (0 to 150 cm) from samples collected prior to planting at representative field locations. Statistical analyses were performed with Statistical Analysis System (SAS Institute, 2008).

Soil Sampling and Analysis

Soil samples were collected at 30-cm intervals to a depth of 120 cm in 1987, 180 cm in 1989 and 150 cm in 1999 prior to spring planting and following grain harvest. Soil samples were collected using 2-cm diameter hand probes prior to planting in control (0 applied N) plots of the plot-scale experiments (2 samples composited for each depth) and from 139 of the geo-referenced field locations (one sample for each 30-cm depth) on 13 contiguous ha (1/3 of the field area) of the field-scale study.[a] Following harvest, soil samples were collected using a 5-cm diameter tractor mounted hydraulic probe from all plots and the same field points. Soil was air-dried and ground to pass a 2-mm sieve prior to analyzing for inorganic N. In 1987, nitrate-N was determined by a modification of the procedure described by Chamot et al. (1911), where ammonium hydroxide was used instead of potassium hydroxide. In 1989 and 1999, both soil nitrate- and ammonium-N were determined colorimetrically from 1 M KCl extracts using a Technicon or Lachet autoanalyzer. Subsamples were dried at 105°C to determine gravimetric soil moisture. Total soil N was determined by dry combustion (Leco C/N/S analyzer) from four bulked, 5-cm diameter cores (0 to 10 cm depth) collected at each of the 139 geo-referenced field locations. Net N mineralization was estimated from these samples as one percent of total N.

Plant Sampling and Analysis

Aboveground plant samples were collected following physiological maturity, Haun stage 16 (Haun, 1973), dried at 60°C and weighed. In the plot-scale experiments, ten plants in 1987, and plants from a 1-m section of a middle row in 1989, were harvested from each plot and spikes threshed to separate the grain and to determine grain to straw weight ratios. Grain yield (G$_w$) was obtained by harvesting four (1987) or five (1989) center rows of each plot (1.2 m by 6.0 m) with a plot combine. The aboveground plant and straw biomass were expressed on an area basis from combine harvested grain yield and grain to straw ratios. In the field-scale experiment, aboveground biomass from 2-m^2 areas was harvested from each of the 139 field locations where soil samples were collected and spikes from the

[a] Names are necessary to report factually on available data; however, the USDA neither guarantees nor warrants the standard of the product, and the use of the name by the USDA implies no approval of the product to the exclusion of others that may be suitable.

remainder of the 369 sample locations. Samples were threshed to separate grain from straw, dried and weighed to express grain and straw biomass on an area basis.

In the plot-scale studies, plant samples were ground and digested with a modified Kjeldahl procedure where salicylic acid and sodium thiosulfate were used to include nitrate and nitrite in the digest (Bremner and Mulvaney, 1982). Total N concentration of the digest was determined with indophenol blue (Cataldo et al., 1974). In the field-scale study, ground plant sample N concentrations were determined using dry combustion (Leco C/N/S analyzer). Aboveground N (N_t) and grain N (N_g) were expressed on an area basis from the product of N tissue concentration and above-ground biomass. Protein concentrations were derived by multiplying grain N concentrations by 5.7.

Components of N use Efficiency

Huggins and Pan (2003) defined NUE components and indexes to assess N use from a broad perspective including: (1) major soil and plant physiological processes that effect N use; (2) economic indicators of N inputs to achieve crop performance goals; and (3) environmental indicators of N use including the sustainability of the agricultural resource base and the potential for resource degradation. Abbreviations and definitions for NUE components are summarized in Table 17.1. Determinations of grain yield (G_w), grain N (N_g), aboveground N (N_t) and applied N fertilizer (N_f), were previously described.

Table 17.1. Summary of N use efficiency and index terminology.
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G_w = grain yield
N_{av} = available N
N_g = grain N
N_s = N supply
N_t = aboveground crop N at physiological maturity
N_f = applied N fertilizer
N_{lo} = N loss via leaching, denitrification and volatilization
N_{av}/N_s = N retention efficiency
N_t/N_{av} = available N uptake efficiency
N_t/N_s = N uptake efficiency = $(N_t/N_{av})(N_{av}/N_s)$
G_w/N_{av} = available N use efficiency = $(N_t/N_{av})(G_w/N_t)$
G_w/N_t = N utilization efficiency
N_g/N_t = N harvest index
N_f/N_s = N reliance index
G_w/N_f = N fertilizer utilization efficiency
N_{lo}/N_f = N loss index
N_g/N_f = N balance index = $(N_{lo}/N_f)(N_g/N_{lo})$
N_s/G_w = unit N requirement
G_w/N_s = N use efficiency = $(N_{av}/N_s)(G_w/N_{av}) = (N_f/N_s)(G_w/N_f)$
N_g/N_s = grain N accumulation efficiency = $(N_g/N_{av})(N_{av}/N_s) = (N_g/N_f)(N_f/N_s)$
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Nitrogen use efficiency is defined as harvested grain yield (G_w) divided by N supply (N_s). In the plot-scale studies, N_s was estimated by summation of N_t in control plots (0 applied N), post-harvest soil nitrate in control plots, and applied N for each respective treatment. In the field-scale study, N_s was estimated by summing pre-plant soil residual mineral N (0 to 150 cm), applied N fertilizer and an estimate of net N mineralization based on levels of total soil N (0 to 10 cm). Nitrogen use efficiency is the product of three factors related to soil and crop physiological processes: N retention efficiency (N_{av}/N_s), available N uptake efficiency (N_t/N_{av}), and N utilization efficiency (G_w/N_t). Available N (N_{av}) in plot and field scale studies was estimated from the sum of aboveground plant N (N_t) and inorganic soil N following harvest (N_h). Overall N uptake efficiency (N_t/N_s) and available N use efficiency (G_w/N_{av}) are derived from products of these factors. Nitrogen use efficiency is also the product of two indicators related to utilization of N fertilizer inputs (G_w/N_f) and soil N resource status, the N reliance index (N_f/N_s).

Grain N accumulation efficiency is defined as grain N (N_g) divided by N supply (N_s) and, when divided by N use efficiency provides efficiency components related to grain N concentration and protein. Grain N accumulation efficiency is the product of three soil and crop physiologic factors: N retention efficiency (N_{av}/N_s), available N uptake efficiency (N_t/N_{av}), and N harvest index (N_g/N_t). It can also be partitioned into two fertilizer efficiency factors: N balance index (N_g/N_f) and N reliance index (N_f/N_s). The N balance index was spatially mapped across 37 ha of the CAF using data from the 369 geo-referenced points and inverse-distance squared interpolation (ESRI, ArcGIS, 2008).

Results and Discussion

Grain Yield-Protein Relations

Grain yield and GPC of plot data followed typical response patterns to increasing N supply (Figure 17.1a). Under a high yielding environment (year 1), initial levels of applied N increased yield with little change in GPC. As N supplies increased, yield response diminished and GPC increased. Targeted GPC goals of 140 g kg^{-1} were not achieved in year 1 and N supplies required for greater GPC could have exceeded N requirements for maximum yield, particularly for MP. In contrast, when grain yield was relatively low (year 2), maximum yields were obtained at lower N supplies, overall GPC shifted to greater levels than achieved in year 1, and GPC goals were met at or before maximum yield (Figure 17.1a). Similar yield-protein relationships expressed under high and low yielding environments have been reported for other wheat producing areas (Terman et al., 1969; Benzian and Lane, 1979).
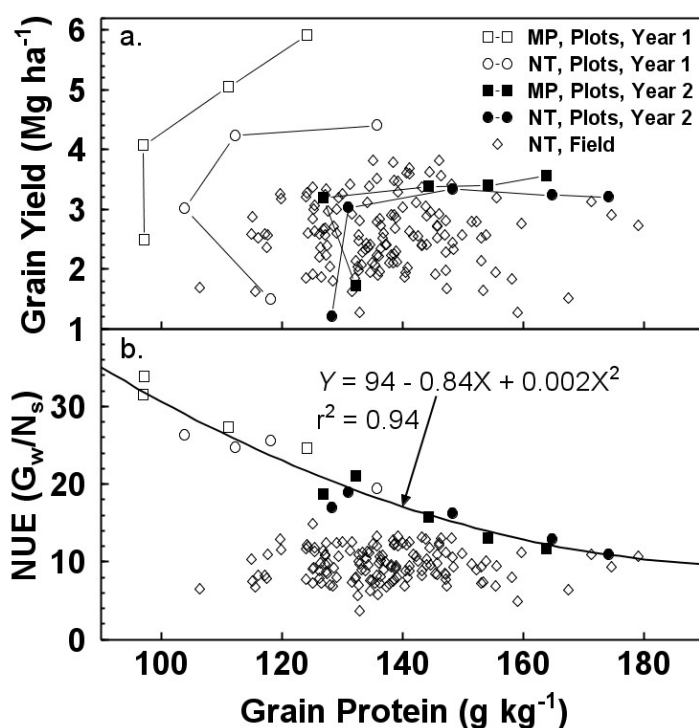
Figure 17.1. Grain yield and N use efficiency (NUE) relationships to grain protein concentration (GPC) in plot- and field-scale data.

Grain yield was reduced in NT as compared to MP in year 1 (Figure 17.1a). However, GPC was increased under NT as grain N accumulation was less affected by tillage than yield. Reduced wheat yields have often been reported in no-tilled as compared to tilled soils in the PNW (Parsons, 1984; Cochran et al., 1982; Elliott et al., 1987). Economic disadvantages of reduced HRS yield under NT could be partially offset by greater GPC and increased marketability. Parsons (1984) reported tillage effects on seasonal N uptake patterns for spring wheat where N uptake was delayed under NT as compared to MP. Late season N uptake could promote grain protein relative to carbohydrate synthesis (Morris and Paulsen, 1985) and contribute to higher GPC as observed in year 1. In year 2, no significant tillage effects on grain yield or protein occurred indicating that tillage impacts on yield-protein relations are potentially greater under higher yielding environments (Figure 17.1a).

No correlation occurred between grain yield and GPC in the field-scale data (Figure 17.1a). Grain yield ranged from 1.3 to 3.8 Mg ha^{-1}, averaging 2.6 Mg ha^{-1} and GPC ranged from 106 to 179 g kg^{-1}, averaging 137 g kg^{-1}, despite uniform N applications targeted for a yield goal of 3.3 Mg ha^{-1} and GPC of 140 g kg^{-1}. Interestingly, many yield-protein scenarios were represented including high grain yield and protein, low yield and protein, high yield and

low protein and low yield and high protein. Lack of correlation between grain yield and GPC in field-scale studies has been previously reported (Reyns et al., 2000; Walley et al., 2001; Skerritt et al., 2002), challenging the premise that grain yield and GPC are inversely related (McNeal et al., 1982; Loffler et al., 1985). In combination with our data, these studies suggest that spatial variation in terrain attributes including soil and topographic characteristics are strong regulators of yield-protein relationships. Furthermore, these data support the contention that large differences in NUE occur within fields (Fiez et al., 1995), potentially influencing N management strategies and the capability to achieve performance goals for HRS.

Nitrogen Use Efficiency

<u>Unit N Requirement</u>

The possibility of unrealized GPC goals at maximum grain yield (Figure 17.1a) indicates that UNR for HRS be based on GPC rather than yield to meet market performance goals. A significant (r^2 = 0.94), negative, relationship occurred between NUE and GPC when plot data from all N rate and tillage treatments were combined across years 1 and 2 (Figure 17.1b.). From this relationship, the UNR (N_s/G_w, or reciprocal of NUE), can be determined for a given GPC goal. For example, approximately 1 kg of N_s is required for every 16 kg of HRS G_w to achieve 140 g kg^{-1} of protein (Figure 17.1b). This UNR for HRS is greater than the 1 kg N_s for every 22 kg grain for SWW where protein goals are not considered and both are currently used in wheat N fertilizer guidelines (Koenig, 2005). An inverse relationship between NUE and GPC indicates that reduced NUE will likely occur as additional N is added to reach greater GPC goals (e.g. as with different classes of wheat). In addition, the comparison of NUE to GPC leads to further analyses based on NUE components to evaluate different scenarios (e.g. different wheat classes, varieties, N management strategies, terrain attributes or environments).

In contrast to the plot-scale studies, no relationship between NUE and GPC occurred in the field-scale experiment (Figure 17.1b). NUE ranged from 4 to 15 kg kg^{-1} due to high rates of applied N and low grain yields, but in contrast to the plot data, low NUE did not necessarily result in greater GPC. The inconsistency between plot- and field-derived data indicates that some components of NUE were quite different within given field locations than those expressed in the plot-scale experiments. Considering that plot-scale studies were conducted on favorable soil and landscape positions where efficiencies in N use would likely approach maximum values for a given field, the plot-scale data likely serve as an upper bound of NUE as shown in Figure 17.1b. From these data we concluded that: (1) direct application of a UNR derived from plot-scale experiments to field-scales may not result in achieving HRS performance goals; (2) field situations where low NUE and GPC occur are likely unsuitable for HRS production unless management strategies can be devised that improve NUE and GPC; and (3) further analysis of NUE components could

identify where differences in NUE between field- and plot-scale experiments arise and guide the development of improved N management strategies.

<u>Nitrogen Utilization Efficiency</u>

To aid further analyses of factors contributing to NUE variability, NUE (G_w/N_s) was partitioned into two main factors: N utilization efficiency (G_w/N_t) and N uptake efficiency (N_t/N_s) (Figure 17.2). Interestingly, N utilization efficiencies resulting from plot and field-scale studies were represented by a single regression line (r^2=0.84), negatively correlated with GPC (Figure 17.2a). N utilization efficiencies often decrease with increasing levels of applied N (Huggins and Pan, 1993), and GPC goals for HRS are obtained as aboveground N increases relative to grain yield, thereby reducing N utilization efficiency. The negative relationship between N utilization efficiency and GPC appears to be predictive as it occurred across different years, treatments and field environments with GPC goals of 140 g kg^{-1} met when N utilization efficiency was reduced to less than 34 kg kg^{-1}. This supports the assertion that once N is taken up by the crop, physiological N use efficiencies follow a predictable progression within the environments represented by these studies.
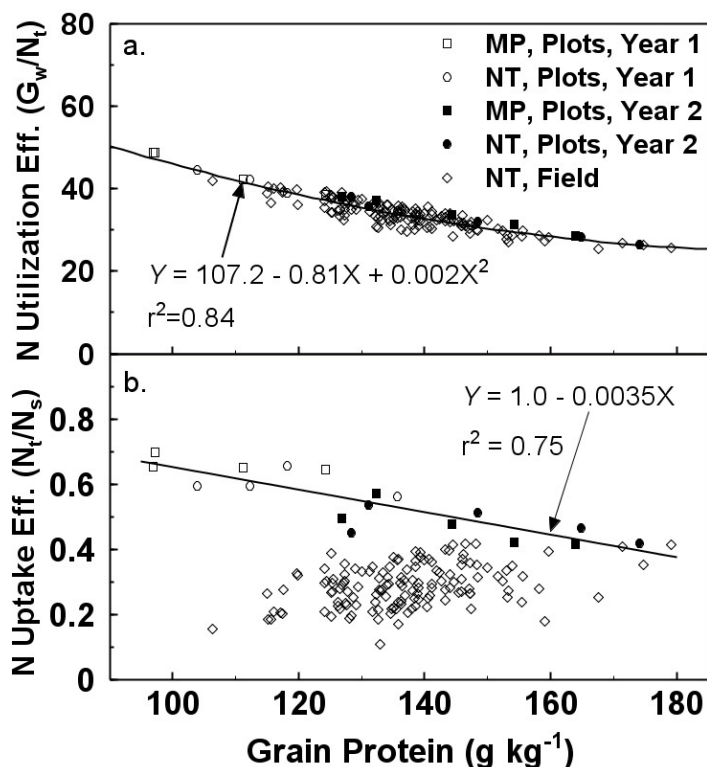

Figure 17.2. N utilization and uptake efficiency relationships to grain protein concentration (GPC) in plot- and field-scale data.

Further insights into the inverse relationship between N utilization efficiency and GPC can be gained by evaluating grain N and yield in relation to aboveground N (Figure 17.3). For a given level of aboveground N, grain yield varied significantly, resulting in a wide range of N utilization efficiencies dependent on environmental and management factors in addition to crop N status (Figure 17.3a). In the field-scale study, GPC less than 140 g kg^{-1} occurred across the full range of N_t; however, at locations where N_t was similar but grain yield was more limited, GPC was often greater than 140 g kg^{-1}. These plot and field-scale phenomena are analogous to crop rotation or tillage effects commonly reported for N studies where crop yields differ among treatments at equivalent levels of aboveground N (Baldock et al., 1981; Hargrove et al., 1983; Pierce and Rice, 1988; Huggins and Pan, 2003). Certainly, increasing yield for a given level of N_t (greater N utilization efficiency) is an important overall objective. At the same time, however, as aboveground N increases, the incremental increase in grain yield diminishes, thereby reducing N utilization efficiency, particularly as greater GPC goals are pursued. In contrast to N utilization efficiency, the proportion of aboveground N mobilized to the grain (N harvest index, NHI) was nearly constant (82%) and relatively unaffected by environmental or management factors over a wide range in N_t (Figure 17.3b). Reported NHI for other hard red wheat producing areas in the United Sates have ranged from 32 to 85% (McNeal et al., 1971, Bauer, 1980; Loffler et al., 1985; Wuest and Cassman, 1992; Rao and Dao, 1996). These data show that relatively efficient mobilization of N to the grain occurs under eastern Washington conditions and that further efficiency gains in NHI may be difficult to achieve.
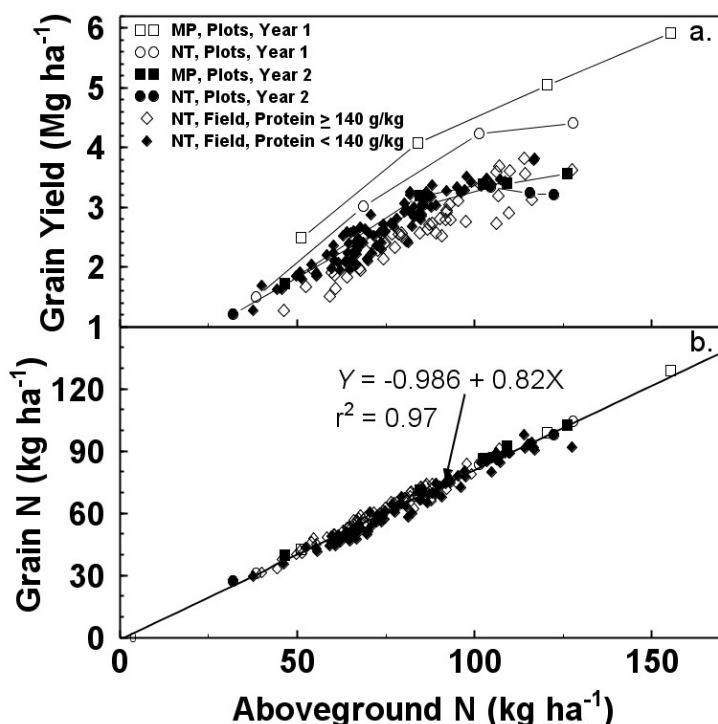
Figure 17.3. Grain yield and N content relationships to aboveground N in plot- and field-scale data.

One consequence of a diminishing response of yield to N_t coupled with a linear increase in N_g with greater N_t (constant NHI) is that GPC will be inversely related to N utilization efficiency as shown in Figure 17.2a. In turn, the nature of this inverse relationship is the major contributing factor that results in the diversity of yield-protein scenarios expressed in Figure 17.1a. Therefore, instead of an inverse relationship between grain yield and protein, the more universal phenomenon consistent with these data is that N utilization efficiency and GPC are inversely related. We conclude that realizing yield and GPC goals will likely be dependent on increasing N_t with the consequence that as N_t increases, N_g will increase linearly (constant NHI) and that grain yield response will have diminishing returns (N utilization efficiency will decrease). Furthermore, these data have important N management implications as increasing N_t to levels required to meet yield and GPC goals will be largely dependent on how efficiently the crop acquires N from available sources (N uptake efficiency).

<u>Nitrogen Uptake Efficiency</u>

N uptake efficiency in the plot-scale data was negatively related to GPC while little relationship to GPC was evident in the field-scale data (Figure 17.2). N uptake efficiencies

approached 70% in plots with 0 applied N (year 1) and decreased to a minimum of 40% at the highest N levels in year 2. Field-scale N uptake efficiencies were generally lower than those achieved in plots and ranged from 12 to 48% of total N supplies. Thus, differences between plot and field-scale NUE-GPC relationships (Figure 17.1b) were primarily due to lower and more variable N uptake efficiencies found within the field. Considerable variability in crop recovery of applied N has been reported in the literature with values ranging from 20 to 87% (Kumar and Goh, 2000). Similar to our findings, values of N uptake efficiency found in farm fields are typically lower then those in research plots (Balasubramanian et al., 2004). Large variations of within-field N uptake efficiency, as found in this study, would likely promote insurance (over) applications of N fertilizer in an attempt to achieve yield and GPC goals. However, field areas with both low N uptake efficiency (<30%) and GPC (<140 g kg^{-1}) are unlikely to obtain greater GPC with increasing amounts of applied N and have a large potential to contribute toward N losses and the degradation of air and water quality. In this situation, site-specific N management strategies may lead to improved N uptake efficiencies in certain field locations. N uptake efficiency is a product of available N uptake efficiency and N retention efficiency and analyses of these NUE components may provide further insights into strategies that could improve overall N uptake efficiency.

Available Nitrogen Uptake Efficiency

Available N uptake efficiency ranged from 46 to 90%, (Figure 17.4) and was negatively related to GPC (r^2=0.47) in the plot-scale data (relationship not shown). In the field-scale data, available N uptake efficiency varied more widely, ranging from 25 to 85% (Figure 17.4) and was not significantly related to GPC. Available N uptake efficiencies of 78% have been reported for soft white winter wheat (Sowers et al., 1994). Low efficiencies could result from N losses or from a poor match between crop demand and N supply leaving high residual levels of soil mineral N following harvest. Low N retention efficiencies indicate the former while high N retention efficiencies combined with low available N uptake efficiencies indicate the latter.
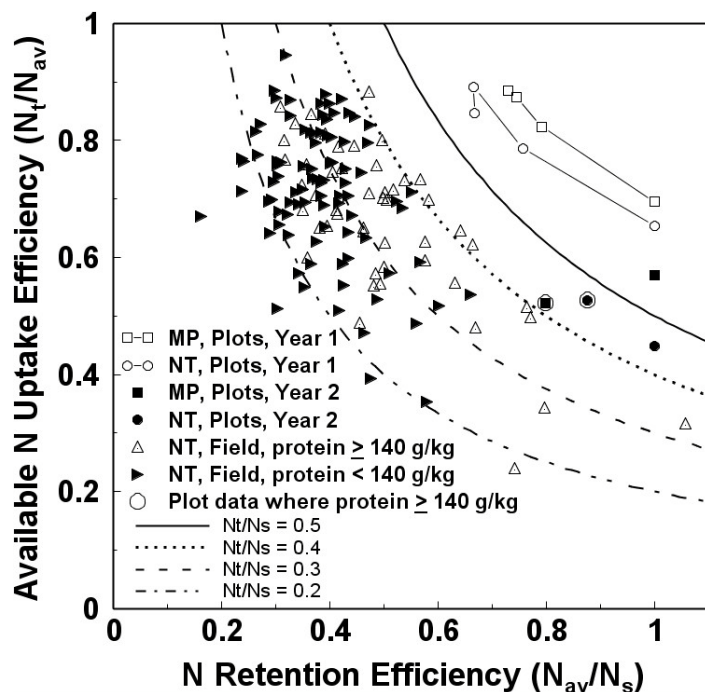
Figure 17.4. Partitioning of N uptake efficiency between available N uptake efficiency and N retention efficiency in plot- and field-scale data.

Nitrogen Retention Efficiency

N retention efficiency in plot-scale data ranged from 70 to 98% and averaged 82% (excluding controls with 0 applied N; Figure 17.4). N retention efficiencies of field-scale data ranged from 20 to over 100%, and were generally lower than plot-scale data averaging 50% (Figure 17.4). N retention efficiencies greater than 100%, as found in one circumstance in the field-scale data, could have resulted from landscape redistribution of soil nitrate or measurement and sampling errors.

Losses of N within cropping systems have been reported to range from 1 to 35% (Kumar and Goh, 2000) with greater losses occurring as N application rates increase (Legg and Meisinger, 1982). High N loss and low fertilizer N recoveries have been reported in Palouse fields, particularly at concave, north-facing topographic positions (Fiez et al., 1995). Here, extensive lateral and vertical movement of soluble agrichemicals has been documented with bromide and dye tracers (Mallawantantri et al.,1996). In addition, restrictions in rooting depth on eroded sites can limit deep water and nitrate extraction, thereby reducing late-season N uptake (Pan and Hopkins, 1991) and potentially, grain protein concentration (Morris and Paulsen, 1985). Our analyses support the conclusion that limiting N losses and improving N uptake efficiencies within fields should be a major priority for developing N management strategies with greater overall NUE.

Classification and Assessment of Wheat Performance

Wheat performance was separated using a dichotomous key into six Performance Classes based on grain protein and NUE criteria (Table 17.2). Performance Classes 1-3 are where wheat achieved GPC market goals of 140 g kg^{-1} or greater, while Classes 4-6 did not obtain this goal. Within grain protein criteria, Classes were further defined based on N uptake efficiency and N retention efficiency. Classes 1 and 4 are defined by N uptake efficiencies equal to or greater than 50% and Classes 2, 3, 5 and 6 as Classes where N uptake efficiency was less than 50%. Use of a 50% N uptake efficiency as a Performance Class defining criteria was based on wheat fertilizer guides where the UNR assumes N uptake efficiencies of 50%. This percentage could be adjusted, if necessary, to meet air and water quality standards or N fertilizer efficiency goals. Where N uptake efficiencies of 50% were not achieved, N retention efficiency was used to further define Performance Classes. Classes 2 and 5 are where N retention efficiencies are greater or equal to 70%, while Classes 3 and 6 are below 70%. These grain protein and NUE criteria were used to classify both field- and plot-scale data and to evaluate HRS performance with respect to yield, GPC and NUE components and indices (Tables 17.1, 17.3 and 17.4).

Table 17.2. Dichotomous key to classification of hard red spring wheat (HRS) performance based on grain protein concentration (GPC) and N use efficiency (NUE) components

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Step		Performance Class
1	GPC is equal to or greater than 140 g/kg and GPC goal is achieved	
	if yes, go to Step 2	
	if no, go to Step 4	
2	N uptake efficiency (N_t/N_s) is equal to or greater than 0.5	
	if yes, ... Class	1
	if no, go to Step 3	
3	N retention efficiency (N_{av}/N_s) is equal to or greater than 0.7	
	if yes, ... Class	2
	if no, ...Class	3
4	N uptake efficiency (N_t/N_s) is equal to or greater than 0.5	
	if yes, ... Class	4
	if no, go to Step 5	
5	N retention efficiency (Nav/Ns) is equal to or greater than 0.7	
	if yes, ... Class	5
	if no, ... Class	6

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The plot-scale data were dominated by wheat Performance Class 4 (Table 17.3). Class 4 represents plots (or field areas) that have relatively high N uptake efficiency, N utilization efficiency and N balance index but require more applied N to achieve grain yield and/or GPC goals. In this case, increasing levels of applied N resulted in large percentages of Performance Classes 1, 2 and 5 with no Class 3 and little Class 6 designations (Table 17.3). Performance Class 1 was typified by high N retention (90%) and available N uptake efficiencies (58%), high N balance index (72%), moderate N utilization efficiencies (31 kg kg^{-1}) and a relatively low N loss index (21%). If Performance Class 1 was achieved on a field-wide basis, it would indicate that crop and N management strategies were well-suited to environmental conditions. The large proportion of Class 2 plots indicated situations where grain yield, GPC and NUE goals would likely be achieved if N rates were reduced. These plots (or field areas) have retained available N, however, N uptake efficiencies are low due to an oversupply of N. No plots occurred in Performance Class 3 and few in Class 6. A relatively small percentage of plots (12%) were in Class 5 with low N uptake but high N retention efficiencies. In these cases, neither yield, protein nor NUE goals were met, possibly due to factors effecting crop health such as soil-borne disease (Cook and Veseth, 1991).

Table 17.3. Wheat yield (G_w), grain protein concentration (GPC) and N use efficiency (NUE) components by Performance Class of plot data across year, tillage treatment and levels of applied N.

NUE Components	Performance Class[†]				
	1	2	4	5	6
n (no. of plots)	32	49	107	25	3
G_w (Mg ha^{-1})	3.2 (1.0)	3.3 (0.3)	3.6 (1.4)	2.4 (1.0)	3.4 (0.8)
GPC (g kg^{-1})	150 (9)	163 (13)	114 (14)	125 (9)	107 (19)
N_s (kg ha^{-1})	187 (59)	272 (32)	142 (61)	147 (66)	161 (57)
N_{av}/N_s	0.90 (0.10)	0.81 (0.06)	0.82 (0.14)	0.85 (0.12)	0.57 (0.04)
N_t/N_{av}	0.62 (0.09)	0.54 (0.03)	0.77 (0.12)	0.52 (0.08)	0.84 (0.05)
N_g/N_t	0.83 (0.03)	0.82 (0.04)	0.82 (0.03)	0.83 (0.03)	0.83 (0.01)
G_w/N_t	31.6 (2.2)	28.9 (3.1)	41.7 (5.3)	38.1 (2.9)	45.3 (8.1)
G_w/N_f	27.0 (5.0)	17.3 (3.1)	45.5 (15.2)	29.2 (6.4)	33.7 (11.4)
N_f/N_s	0.64 (0.05)	0.72 (0.04)	0.59 (0.11)	0.58 (0.07)	0.67 (0.12)
N_g/N_f	0.72 (0.12)	0.49 (0.07)	0.88 (0.23)	0.64 (0.11)	0.61 (0.11)
N_{lo}/N_f	0.18 (0.14)	0.27 (0.08)	0.43 (0.15)	0.41 (0.11)	0.64 (0.04)
N_h (kg ha^{-1})	62 (24)	104 (12)	24 (13)	55 (19)	14 (3)

† Classes based on GPC and NUE criteria in Table 17.2. Performance Class 3 did not occur in plot-scale data. Standard deviation of the mean is in parentheses.

Nitrogen fertilization for the field-scale experiment was based on HRS N requirements (NUE of 16 kg kg^{-1}) determined from the plot data (Figure 17.1b). Achieving grain yield and GPC goals on a field-scale basis using this N fertilization guide is dependent on realizing N utilization efficiencies of 34 kg kg^{-1} or less (Figure 17.2a) and N uptake efficiencies of 50% or more (Figure 17.2b), thereby qualifying for Performance Class 1 (Table 17.2). In the field-scale study, Classes 1, 4 and 5 did not occur while Class 2 occurred on 3%, Class 3 on 33% and Class 6 on 64% of the sampled sites (Table 17.4). Grain yield, N retention efficiency, N fertilizer utilization efficiency and N balance index tended to decline as NUE class increased from 2 to 6, while the N loss index increased from 54 to 105% (Table 17.4). The N reliance index (averaging 62%) and N harvest index (averaging 80%) had the greatest field-scale stability across NUE classes. The high N reliance index was similar to values reported for continuous corn and would likely decrease with the inclusion of legumes in rotation (Huggins and Pan, 2003).

Table 17.4. Wheat yield (G_w), grain protein concentration (GPC) and N use efficiency (NUE) components by Performance Class for field-scale data.

| NUE Components | Performance Class† | | | |
	2	3	6	Field
n (no. of points)	5	44	86	135
G_w (Mg ha^{-1})	2.2 (0.7)	2.7 (0.6)	2.6 (0.5)	2.6 (0.6)
GPC (g kg^{-1})	154 (5.5)	148 (7.8)	130 (7.1)	137 (11.4)
N_s (kg ha^{-1})	248 (19)	273 (35)	273 (35)	272 (35)
N_{av}/N_s	0.83 (0.13)	0.46 (0.09)	0.39 (0.08)	0.43 (0.15)
N_t/N_{av}	0.38 (0.12)	0.69 (0.10)	0.71 (0.12)	0.69 (0.13)
N_g/N_t	0.76 (0.04)	0.80 (0.03)	0.80 (0.04)	0.80 (0.04)
G_w/N_t	28.4 (1.9)	31.1 (2.2)	35.1 (2.7)	33.6 (3.3)
G_w/N_f	13.7 (4.5)	16.5 (3.7)	15.8 (3.2)	16.0 (3.4)
N_f/N_s	0.66 (0.05)	0.60 (0.07)	0.60 (0.07)	0.61 (0.07)
N_g/N_f	0.37 (0.12)	0.43 (0.09)	0.36 (0.08)	0.38 (0.09)
N_{lo}/N_f	0.26 (0.21)	0.91 (0.20)	1.03 (0.22)	0.95 (0.29)
N_h (kg ha^{-1})	129 (44)	39 (18)	34 (23)	40 (33)

†Classes based on GPC and NUE criteria in Table 17.2. Performance Classes 1, 4 and 5 did not occur in field-scale data. Standard deviation of the mean is in parentheses.
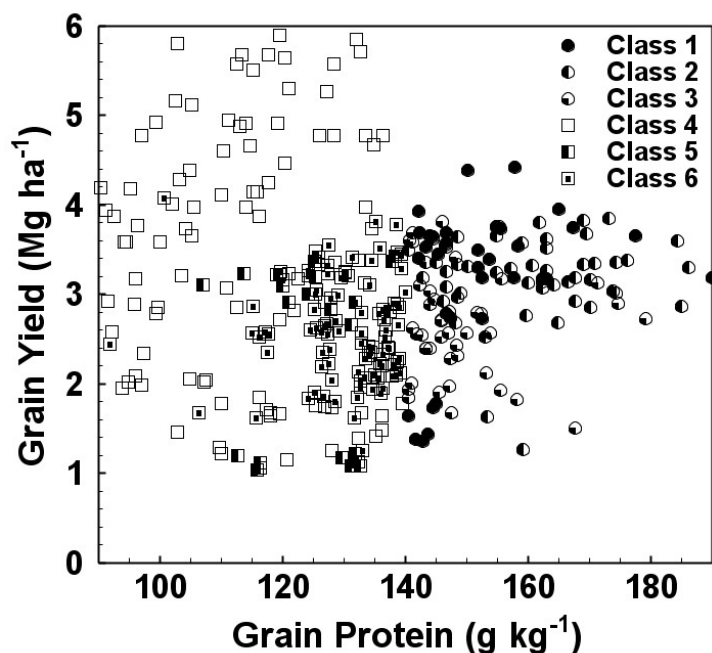
Figure 17.5. Relationship between grain yield and grain protein concentration (GPC) by wheat Performance Class for combined plot- and field-scale data.

Performance Class 3 was typified by relatively low grain yield and high GPC, low N uptake efficiency (31%), low N fertilizer utilization (14.9 kg kg^{-1}) and N balance index (0.37 kg kg^{-1}) (Table 17.4, Figure 17.6). Cropping systems with N balance indices of less than 1 kg kg^{-1} indicate that N applications are compensating for N losses and could be improved by inclusion of legumes (Huggins and Pan, 2003). Improved environmental suitability for HRS production in locations with Performance Class 3 is dependent on determining realistic grain yield goals (lower than field average) and adjusting N rates accordingly, as well as improving N utilization efficiency and N balance index through crop rotation design.
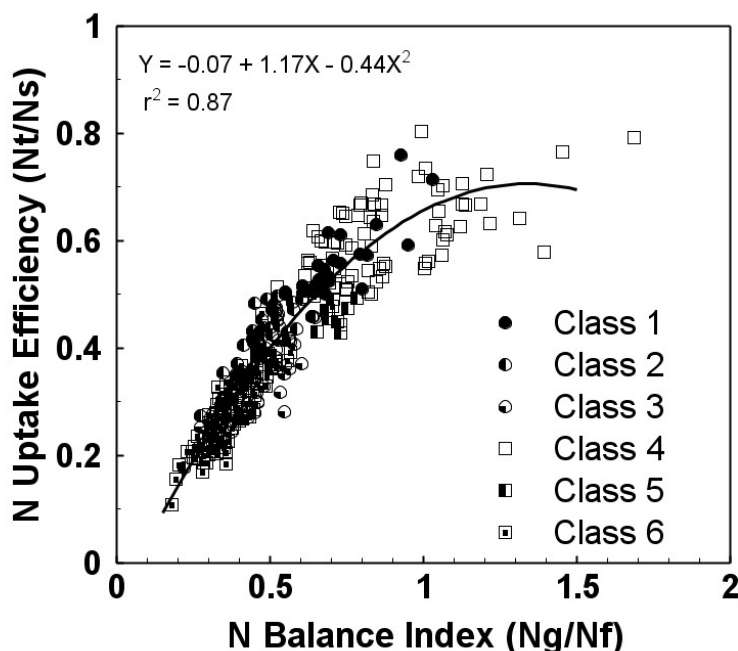
Figure 17.6. Relationship between N uptake efficiency and N balance index by wheat Performance Class for combined plot- and field-scale data.

The low GPC of Performance Classes 2 and 4 (Figure 17.6) is difficult to rectify by simply increasing N rates due to the low N uptake efficiencies (Table 17.4). Therefore, improvements in N timing, form, placement or other cropping practice such as rotation or tillage will need to be considered for possible improvements in N retention and uptake efficiency. The extremes in NUE found under uniform N applications in the field setting underscore the need to develop site-specific N management strategies. Furthermore, the environmental suitability of producing wheat with high GPC in this region is likely reliant on the successful application of precision farming technologies.

Field assessment of N uptake efficiency as used for determining wheat performance (Table 17.2) requires quantification of total N uptake and N supply. These variables are currently difficult to evaluate in the field; however, available precision agricultural technologies could collect data for estimating N uptake efficiency. Combine mounted grain yield monitors and grain quality sensors for evaluating protein concentrations supply data required to estimate grain N removal (N_g) at geo-referenced field locations (Long et al., 2008). Combined with applied N data, given by variable rate fertilizer application technologies, geo-referenced data

for N_g and N_f could be collected at the field scale enabling calculation of an N balance index. A significant quadratic relationship occurred between N balance index and N uptake efficiency for plot and field data (Figure 17.6). This relationship likely occurs as a consequence of two factors: (1) the N harvest index is relatively consistent across field conditions and plot treatments, consequently N_t is strongly related to N_g (Tables 17.3 and 17.4; Figure 17.3b); and (2) N fertilizer (N_f) is a major component of overall N supplies (N_s), and crop N uptake efficiencies of fertilizer-derived N are similar to soil-derived N. The quadratic relationship suggests that N uptake efficiencies for HRS used in these studies have an upper bound of approximately 80% even as the N balance index continues to increase as soil-derived N becomes a greater proportion of overall N supplies in treatments with little or no applied N fertilizer. Also apparent are the distribution of wheat Performance Classes as they are derived, in part, by N uptake efficiency (Figure 17.6, Table 17.2). In this case, an N balance index greater than 0.6 approximates an N uptake efficiency greater than 0.5 and would include Classes 1 and 4. Deviations are apparent, however, and a few Class 2 and 5 locations occurred at N balance indices between 0.6 and 0.8 (Figure 17.6). The N balance index values derived from N fertilizer, grain yield and protein data showed distinct field patterns (Figure 17.7) and suggest that these data could be used in formulating and evaluating different precision N strategies that include yield, protein and N efficiency goals.
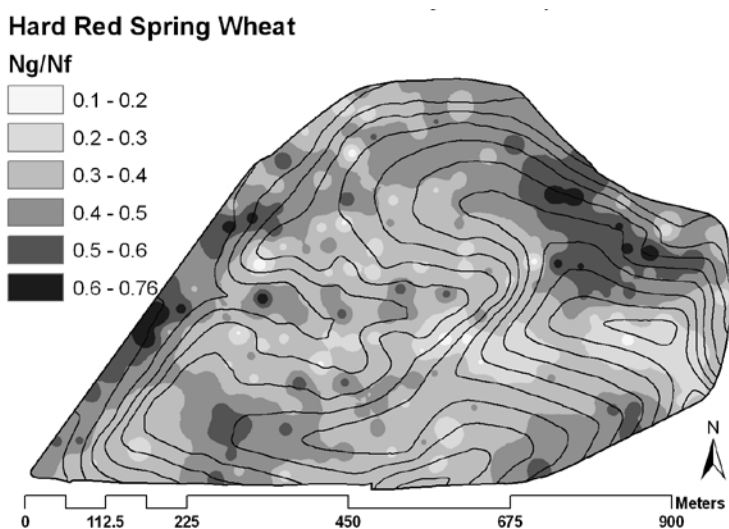

Figure 17.7. Spatial map of N balance index (N_g/N_f) across 37 ha Cook Agronomy Farm. Contour intervals are 3 m.

Conclusion

Tremendous field-scale variation in HRS grain yield, GPC and NUE make it difficult to apply plot-derived N management data when assessing N requirements and management

strategies. Overall, the field- and plot-scale data for HRS indicated that: (1) N requirements and management strategies based on small-scale plot data cannot be extrapolated to more diverse field-scale conditions; (2) uniform field-scale applications of N are not likely to achieve field-scale goals of grain yield, GPC and NUE; (3) a large proportion of the field may not be suitable for HRS production unless site-specific N management strategies that improve NUE are devised; (4) NUE components and indices can be used to evaluate crop grain yield-GPC relations and to diagnose field areas with over or under application of N, poor N utilization or uptake efficiencies, and areas with significant N loss; and (5) devising N requirements and management strategies for HRS should use a combination of plot- and field-scale data.

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