NITROGEN MANAGEMENT

Economically Optimal Nitrogen Fertilization for Yield and Protein in Hard Red Spring Wheat

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ABSTRACT

This analysis determines profit-maximizing N fertilization levels of hard red spring wheat (HRSW) (*Triticum aestivum* L.) for various wheat prices, N prices, and protein-based HRSW price premium/discount (P/D) structures for southeastern Washington data. Fertilizer response data consisting of rates of N fertilization (kg ha^{-1}), grain yield (kg ha^{-1}), and grain protein (g kg^{-1}) were used to statistically estimate regression relationships that predicted yield and protein in response to N. Experiments were located near Pullman, WA (550 mm average annual precipitation). All predicted net return maximizing N, protein, and yield levels were within the data range. Increasing P/D incentives for protein increased optimal N, the expected economic result. At the high P/D structures, the P/D structure dominated N and wheat prices in determining optimal N application levels. Overall, net return–maximizing yields varied only modestly with changes in both N and wheat price in this data set. However, in all scenarios, as P/D incentives increased, net return–maximizing N levels were beyond the level that resulted in maximum yield. At the two lowest P/D structures, which provided the lowest reward for protein, it was most profitable to fertilize for slightly less than 140 g kg^{-1} expected protein. These results indicate that it is not always profitable to use 14% protein as an N fertilization goal.

PRODUCTION OF HRSW by dryland farmers in the Pacific Northwest has increased in recent years, possibly due to low prices for soft white wheat relative to production costs. Hard red spring wheat has maintained a varying price advantage over soft white wheat in recent years (Janosky, 1999; USDA, unpublished, 2001). Variety trials near Pullman, WA, from 1997 to 2001 show that HRSW yield has averaged 202 kg ha^{-1} less than soft white spring wheat (Burns et al., 2001). However, recent trends with newer varieties show HRSW yields gaining on soft white spring wheat.

Profitable fertilization and other management practices of continuous HRSW also promote environmental objectives. Annual cropping of HRSW as a substitute for traditional winter wheat–summer fallow in lower-rainfall cropping regions can reduce wind erosion and air pollution in the semiarid Pacific Northwest. Lee (1998) estimated that annual spring grain cropping of all current dryland fallow would reduce concentrations of suspended dust particles 10 μm and smaller, by up to 95% during extreme wind events, in east-central Washington. Annual cropping leaves more surface residue and/or roughness that protects against wind erosion. Shorter periods between crops also reduce the time period that the soil is unprotected from wind erosion (Papendick, 1998). However, Young et al. (2001) report that continuous no-till (NT) HRSW in this region has been less profitable than wheat–fallow rotations based on standard fertilization practices. If annual production of HRSW with optimal N fertilization can be shown to be profitable, both economic and environmental objectives could be served.

The price that a producer receives for HRSW, unlike soft white wheat, is influenced by protein concentration (g kg^{-1}). Premiums (\$ Mg^{-1}) are added to the base wheat price (reported at 140 g kg^{-1} protein) for each 2.5 g kg^{-1} above 140 g kg^{-1} protein and discounts (\$ Mg^{-1}) subtracted from the base price for each 2.5 g kg^{-1} below 140 g kg^{-1} protein. Historically, discounts have been weighted more heavily than premiums. Table 1 reports regional yearly average price and corresponding P/D structure for 1991–1992 through 2000–2001 (USDA, unpublished, 2001). Note that premiums vary greatly from \$0.37 Mg^{-1} to \$4.78 Mg^{-1} and discounts from \$1.10 Mg^{-1} to \$8.54 Mg^{-1} over this 10-yr period.

Since both yield and protein affect profit, economically motivated growers will desire to apply N fertilizer to HRSW at rates that maximize profit considering both yield and protein. The grower controls some factors affecting yield and protein: N application rate, seeding rate, and variety. Moisture available to the dryland crop is a very important uncontrollable factor that determines protein content. While preplant soil moisture and preplant soil NO_3 are measurable, growing season precipitation is beyond the dryland grower's control.

Vaughan et al. (1990) found that a quadratic relationship existed between hard red winter wheat yield and both fall- and spring-applied N in eastern Colorado. A quadratic relationship was found between protein and fall-applied N and a linear relationship between protein and spring-applied N. This Colorado research showed grain yield response to N fertilization depended on precipitation and residual soil NO_3 while grain protein responded to N fertilization regardless of precipitation and soil NO_3 levels. High levels of soil NO_3 and low moisture

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Abbreviations: CT, conventional tillage; HRSW, hard red spring wheat; NT, no-tillage; P/D, premium/discount.

Table 1. Annual average hard red spring wheat prices with corresponding protein premiums and discounts reported in \$ Mg^{-1} per 2.5 g kg^{-1} above or below 140 g kg^{-1} protein.†

Production year	Price	Premium	Discount
		\$ Mg^{-1}	
1991–1992	\$156.48	\$0.37	\$1.10
1992–1993	\$164.93	\$2.39	\$3.49
1993–1994	\$202.40	\$4.78	\$8.54
1994–1995	\$173.75	\$2.20	\$3.21
1995–1996	\$225.91	\$1.93	\$2.39
1996–1997	\$198.73	\$1.38	\$2.02
1997–1998	\$172.65	\$1.74	\$2.66
1998–1999	\$154.65	\$1.38	\$2.39
1999–2000	\$147.67	\$2.11	\$3.31
2000–2001	\$150.97	\$1.65	\$2.66

† Source: USDA Grain Market News (unpublished, 2001).

conditions also increased grain protein response to N fertilization.

Other studies have also shown the effect of N on yield and protein content of grain depends on the amount of water available for growth (Clarke et al., 1990; Rasmussen and Rohde, 1991; Terman et al., 1969; Whitfield and Smith, 1992). If water and other factors of growth are sufficient, the first effect of applied N is to increase yield. As N is absorbed in excess of vegetative needs, it is applied to protein content of the grain (Terman et al., 1969).

Economic studies have derived profit-maximizing input rates for other crops when inputs affect both yield and quality. Van Tassell et al. (1996) derived profit-maximizing N application rates for sugar beet (*Beta vulgaris* L.) production that maximized profit considering root yield, sucrose content, and fertilizer cost. Profit was computed as gross revenue (sucrose-dependent price of sugar beet times root yield) less total costs (ownership costs of the N application method, variable costs, and price of N times quantity of N). Norton et al. (1997) estimated the profit-maximizing N fertilization of grass hay considering yield and protein. This model calculated net value of grass hay per acre, adjusting the price for higher or lower nutritional quality (digestible protein) and subtracting fertilization and harvesting costs. Yield and digestible protein were estimated functions of applied N and harvest date.

No previous economic analysis was found on optimal N fertilization for yield and protein in HRSW. However, research by Vaughan et al. (1990) on hard red winter wheat concluded that at moderate protein premiums of \$1.10 Mg^{-1} per 2.5 g kg^{-1} above 120 g kg^{-1}, additional N applied for the purpose of increasing grain protein was not profitable unless application costs were avoidable by being part of a regular tillage practice. Vaughan et al. (1990) did not examine sensitivity of profit-maximizing N rates to a variety of wheat prices and P/D structures.

The objective of this research is to determine economically optimal N fertilization levels of HRSW for various wheat prices, N prices, and protein P/D structures based on yield and protein response to applied N for southeastern Washington. The sensitivity of economically optimal N fertilization levels to systematic changes in wheat price, N price, and P/D structure is portrayed graphically and in tables.

Table 2. Average yield and protein by N level for 1987 and 1989.

Year	N	Yield	Protein
	kg ha^{-1}	Mg ha^{-1}	g kg^{-1}
1987	0	1.983	107.70
	56	3.539	100.43
	112	4.629	111.67
	168	4.146	129.99
1989	0	1.458	130.33
	90	3.107	128.97
	134	3.354	146.38
	179	3.309	159.53
	224	3.378	169.05

MATERIALS AND METHODS

Overview of Analysis

Field experiment data of HRSW consisting of rates of N fertilization (kg ha^{-1}), grain yield (kg ha^{-1}), and grain protein (g kg^{-1}) were used to estimate regression models showing yield and protein response to applied N. Using growers' expectations of the price of HRSW, P/D structures for protein, and the price of N, the rate of N that maximized net returns (returns above N cost) was then calculated. Recommended N application rates and associated protein, yield, and net return (\$ ha^{-1}) for the study region were found for 30 combinations of wheat price, P/D structure, and N price.

Experiment Description

The field experiments supplying the data for this analysis used randomized complete block designs with four replications conducted over two sites and growing seasons, 1987 and 1989. The sites were near Pullman, WA (550 mm average annual precipitation). The soil types were slightly different, but both were in landscape positions that would have high yield potential. Differences in growing season precipitation favored the 1987 crop.

Table 2 reports average yield and protein by N application level and year for the data set. One of the 216 total plots was discarded due to incomplete data. Nitrogen rates were 0, 56, 112, and 168 kg ha^{-1} in the 1987 experiment and 0, 90, 134, 179, and 224 kg ha^{-1} in the 1989 experiment, applied as ammonium nitrate (NH_4N0_3) banded 10 cm below the seed at planting (Huggins 1991). Calcium sulfate ($CaSo_4$) was banded with the N at rates of 0, 17, and 34 kg sulfur ha^{-1} in 1987 and 1989. Triple super phosphate [$Ca(H_2PO_4)_2$] at a rate of 22 kg ha^{-1} phosphate was banded with the N in 1989.

Hard red spring wheat variety 'WB 906R' was grown under rainfed conditions on Latah silt loam (fine, mixed, mesic Xeric Argialboll) in the 1987 experiment and on a Palouse silt loam (fine-silty, mixed, mesic Pachic Ultic Haploxeroll) in 1989. Hard red spring wheat was grown in both NT and conventional tillage (CT) regimes, following winter wheat in both years. Surface winter wheat residues on the NT plots were estimated before planting at 4000 kg ha^{-1} in 1987 and 1989. No-tillage consisted of planting directly into standing winter wheat stubble. Conventional tillage consisted of moldboard plowing in the fall followed by spring disking, harrowing, and planting (Huggins and Pan, 1993). Hard red spring wheat was seeded at 85 kg ha^{-1} on 10 Apr. 1987 and at 95 kg ha^{-1} on 18 Apr. 1989 using a NT drill equipped with fluted coulters and fertilizer shanks preceding double-disk seed openers. Row spacing was 0.3 m in 1987 and 0.2 m in 1989 on plot sizes of 1.8 by 12.2 m (Huggins, 1991).

Soil samples were collected before spring seeding. Two plots from each replication in each year were sampled to a depth of 1.2 m in 1987 and 1.8 m in 1989. This yielded soil samples from 16 of the 216 total plots over 2 yr. Soil samples were analyzed for nitrate N (NO_3) and gravimetric soil moisture. Preplant soil NO_3 to a depth of 1.2 m averaged 69.8 kg ha^{-1} in 1987 and 30.4 kg ha^{-1} in 1989. Preplant soil moisture to a depth of 1.2 m averaged 56.6 cm in 1987 and 44.51 cm in 1989. A plot combine was used to harvest four center rows in 1987 and five center rows in 1989 of each plot to determine grain yield. Grain protein concentrations were obtained by multiplying grain N concentrations by 5.7. Grain N was determined using a modified Kjeldahl procedure, and N concentration determined by indophenol blue.

Statistical and Economic Methods

Though the data were collected in 1987 and 1989, analysis for economically optimal N fertilization of HRSW had not been completed with this data, nor was any more recent data available for the region. In addition, no similar analysis of economically optimal fertilization of HRSW was found for other regions. To show the effects of changing economic conditions on optimal N fertilization, the analysis considered high, intermediate, and low grain prices, five P/D structures, and high and low N prices. The range of P/D structures is based on 10 yr of historical Port of Portland price data. Premiums and discounts are in \$ Mg^{-1} per 2.5 g kg^{-1} above or below 140 g kg^{-1} protein. The HRSW prices were reported by USDA at Portland, OR. To convert these to southeastern Washington farm gate prices, they are reduced by \$14.70 Mg^{-1} to reflect transportation and handling costs to Portland. The N prices (adjusted to 100% N) are the high (2001) and low (1999) annual average prices paid by Pacific Northwest region farmers for anhydrous ammonia in the years 1997 to 2001 (WASS, 2001).

Multiple-regression analysis of the experimental data was used to estimate the statistical relationships between yield and applied N and protein and applied N. Following Vaughan et al. (1990), the production function for yield in response to N was expected to be quadratic with a non-zero intercept and declining marginal productivity. For this decision analysis problem, it is appropriate to retain the variation in yield due to different precipitation over the 2 yr in the error term, as opposed to including variables for years. A farmer cannot know, at the time of fertilizing, the amount of growing season precipitation; therefore, optimal fertilizer levels need to be based on yield responses from average growing season precipitation.

The response function for protein was expected to be linear with a non-zero intercept and protein continuing to increase at N levels beyond maximum yield. The yield regression estimation model was adjusted for heteroskedasticity using Generalized Least Squares because a significant difference in the variance in yield between years was found using the Goldfeld–Quandt test (Hill et al.2001). The low sampling intensity (only 16 of 216 plots) for soil nitrate and soil moisture in the experiment precluded use of these as explanatory variables in the analysis of protein and yield response.

The computed optimal fertilization levels are those that maximize expected returns over fertilizer costs. Estimated yield and protein models were integrated into a net return (\$ ha^{-1}) function conditional on expected grain price, N price, and P/D structure. Iterative use of a spreadsheet over 1 kg ha^{-1} N intervals identified the N rate that maximized expected net return for selected HRSW prices, protein P/D structures, and N prices. The analysis also identified the wheat yield and protein level associated with each net return–maximizing N level.

RESULTS AND DISCUSSION

Expressions [1] and [2] report regression equations for grain yield and grain protein responses to applied N. Equation [3] integrates Eq. [1] and [2] into a net returns function (returns above N costs). Coefficient t statistics are in parentheses. Adjusted R^2's show equation goodness of fit.

1. Grain Yield

$$\begin{array}{l} Y = 1.86012 + 0.02741N - 0.00009N^2 - 0.43923T; \\ \quad (18.73) \quad (15.11) \quad (-11.04) \quad (-5.17) \\ \quad \text{Adj. } R^2 = 0.63 \end{array}$$

2. Grain Protein

$$\begin{array}{l} P = 104.13 + 0.22N + 7.49T; \qquad \text{Adj. } R^2 = 0.46 \\ \quad (41.43) \quad (13.24) \quad (3.01) \end{array}$$

3. Net Returns Function

$$\text{NR} = (\text{Pw} \times Y) - \text{Pn} \times N + \{[(P - 140)/2.5 \times (\text{Prem. or Disc.})] \times Y\}$$

where

Y = grain yield (Mg ha^{-1})
P = grain protein (g kg^{-1})
N = preplant-applied N (kg ha^{-1})
T = binary variable for tillage (0 = CT, 1 = NT)
NR = returns above N costs (\$ ha^{-1})
Prem. = \$ Mg^{-1} for each 2.5 g kg^{-1} above 140 g kg^{-1} protein
Disc. = \$ Mg^{-1} for each 2.5 g kg^{-1} below 140 g kg^{-1} protein
Pw = price of HRSW (\$ Mg^{-1})
Pn = price N fertilizer (\$ kg^{-1})

The relatively high t statistics of all the regression coefficients confirm that applied N has a statistically significant impact on both yield and protein. The adjusted R^2's of the functions are reasonable given the number of explanatory variables and data sites. Data from only two sites provide less variability to be explained vs. several sites as in Vaughan et al. (1990), who used data from 19 sites and had a larger number of explanatory variables. The positive intercept and concave quadratic form of the yield function (Fig. 1) shows expected positive yield without applied N and diminishing marginal wheat yield to applied N. The positive intercept and linear form of the protein function (Fig. 2) is consistent with other research in which protein is positive at zero spring-applied N and responds linearly to additional N (Vaughan et al., 1990). The binary variable for tillage allows for a negative or positive impact of tillage on yield and protein. In this case, expected NT yields were 0.439 Mg ha^{-1} below CT and expected protein concentrations 7.49 g kg^{-1} above CT. Due to the additive nature of these binary variables, they simply shift the response functions for yield and protein and do not change their shape. Because CT is the dominant practice in the region, results are reported below only for CT. The general patterns of the results were the same for NT; how-

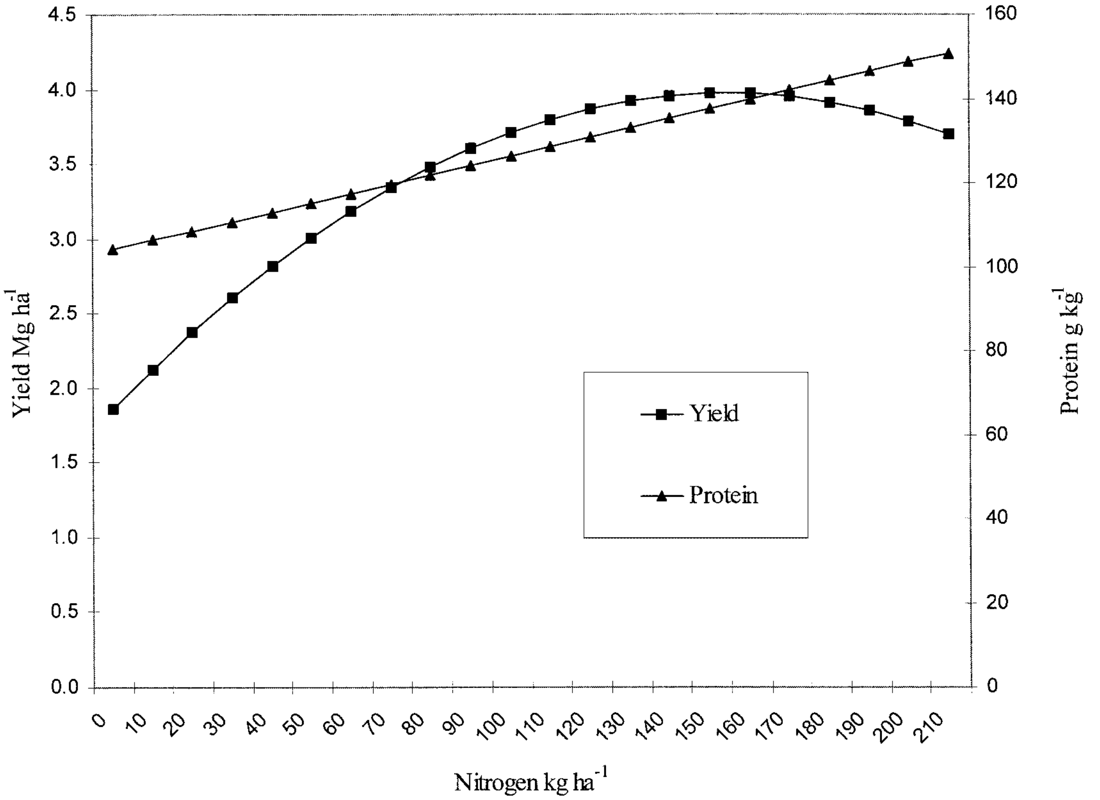

Fig. 1. Grain yield and protein response to applied N per Eq. [1] and [2], respectively.

ever, N rates, net returns, and yields were slightly lower for NT than CT while protein levels were slightly higher.

Figure 2 illustrates the influence of wheat price, N price, and P/D on the shape of the NR functions using four combinations of wheat price, N price, and P/D. As expected, lower wheat prices generate lower NR functions in Fig. 2. Figure 2 also shows that at higher P/D structures, maximum profit is achieved at higher levels of N, for both wheat and input price combinations. Higher P/D structures while holding wheat price and N price constant lead to steeply ascending net returns as N and protein increase until the 140 g kg^{-1} protein threshold is reached. Inadequate fertilization resulting in protein below the threshold imposes a smaller NR penalty

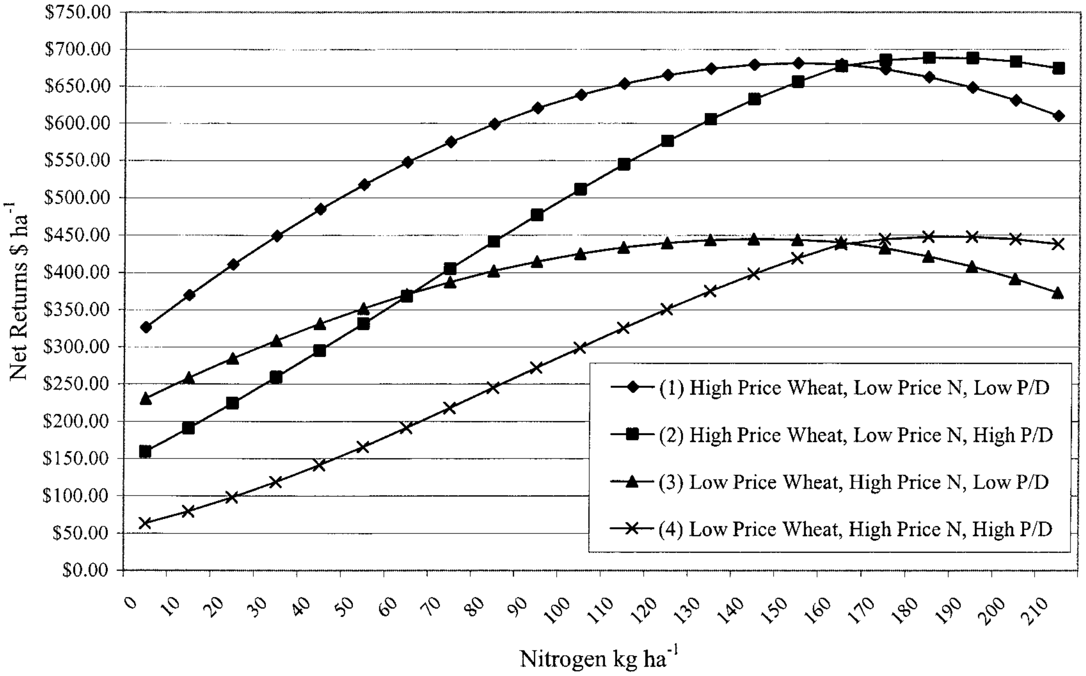

Fig. 2. Net returns response to N fertilization. Note P/D = protein premium/discount.

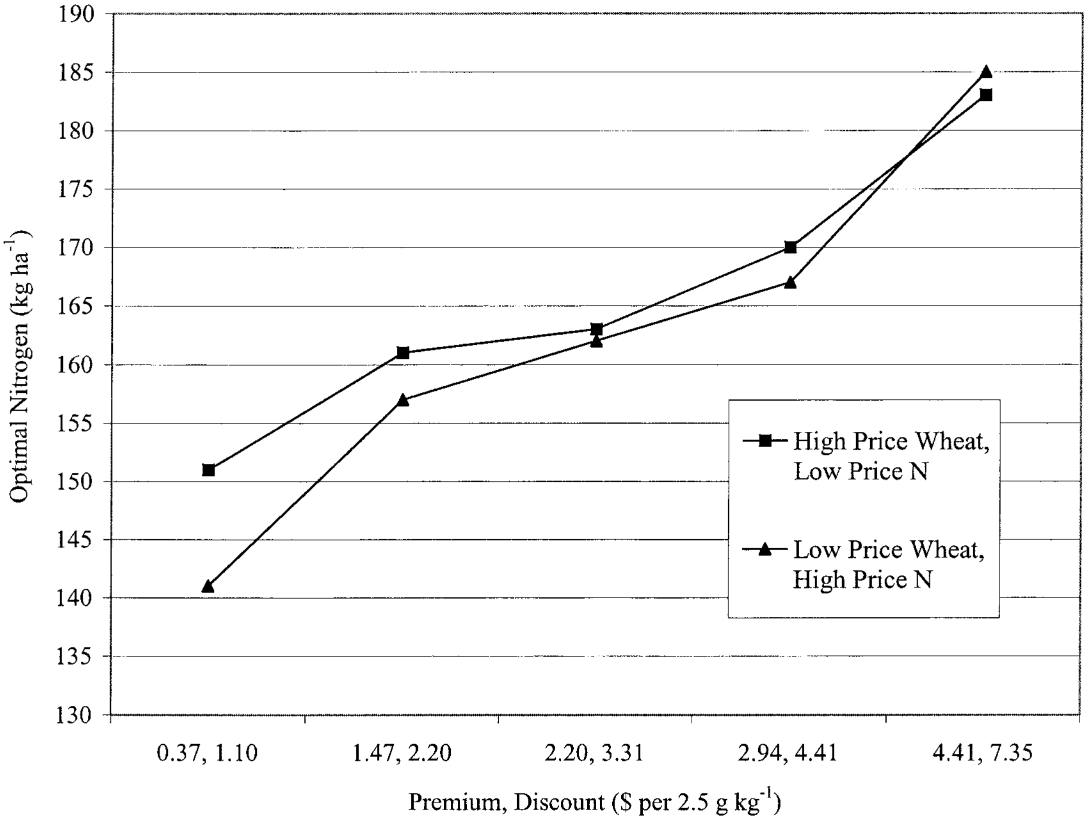

Fig. 3. Economically optimal N levels in conventional-tillage hard red spring wheat for varying premium and discount (P/D) price structures.

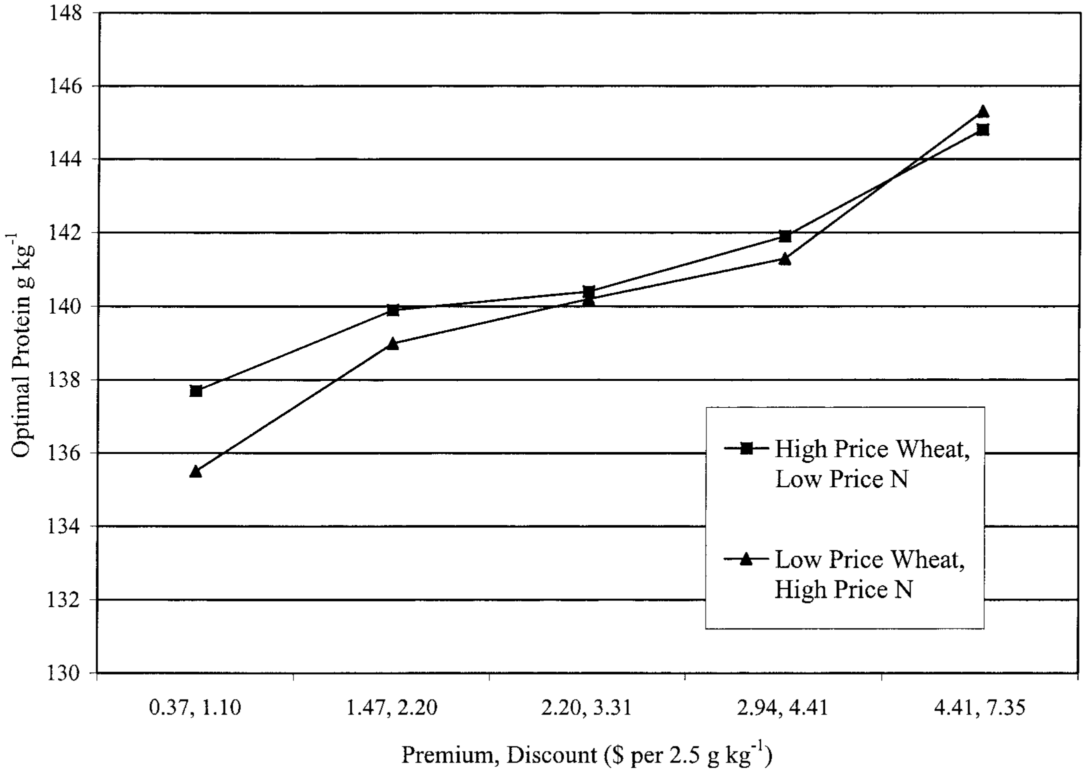

Fig. 4. Economically optimal protein levels in conventional-tillage hard red spring wheat for varying premium and discount (P/D) price structures.

Table 3. Optimal N fertilization rates and resulting net returns (NR), grain protein, and yield by varying protein premiums and discounts for conventional tillage hard red spring wheat under the following price conditions: high-price wheat and low-price N.

N price = $0.49 kg^{-1}			Wheat price = $191.10 Mg^{-1}		
Premium	Discount	Optimal	Maximum	Optimal	Optimal
—— $ Mg^{-1} ——		N, kg ha^{-1}	NR, $ ha^{-1}	protein, g kg^{-1}	yield, Mg ha^{-1}
$0.37	$1.10	151	$681.27	137.7	3.973
$1.47	$2.20	161	$679.55	139.9	3.970
$2.20	$3.31	163	$679.59	140.4	3.967
$2.94	$4.41	170	$680.92	141.9	3.952
$4.41	$7.35	183	$688.94	144.8	3.901

Table 5. Optimal N fertilization rates and resulting net returns (NR), grain protein, and yield by varying protein premiums and discounts for conventional tillage hard red spring wheat under the following price conditions: low-price wheat and low-price N.

N price = $0.49 kg^{-1}			Wheat price = $139.65 Mg^{-1}		
Premium	Discount	Optimal	Maximum	Optimal	Optimal
—— $ Mg^{-1} ——		N, kg ha^{-1}	NR, $ ha^{-1}	protein, g kg^{-1}	yield, Mg ha^{-1}
$0.37	$1.10	150	$476.86	137.5	3.972
$1.47	$2.20	161	$475.29	139.9	3.970
$2.20	$3.31	165	$475.56	140.8	3.964
$2.94	$4.41	175	$477.98	143.0	3.936
$4.41	$7.35	192	$489.54	146.8	3.848

with low P/Ds as shown by the initial advantages of Curve 1 over 2 and Curve 3 over 4. After N achieves 14% protein, the NR curve flattens due to the relatively greater magnitude of discounts compared with premiums.

Figures 3 and 4 plot economically optimal N and protein levels, respectively, over the five selected P/D structures for a high wheat price/low N price scenario and a low wheat price/high N price scenario for CT HRSW. At lower P/D structures, maximum net return is achieved by fertilizing for slightly less than 140 g kg^{-1} protein for both high and low N prices (Fig. 4). These results indicate that it is not always profitable to use 14% protein as an N fertilization goal. Figures 3 and 4 reveal that wide ranges in wheat and N prices have relatively modest effects on optimal N and resulting protein concentration for given P/D structures. However, wheat price and N price at lower P/D structures have a larger impact on optimal N and resulting protein levels than at higher P/D structures. This relationship is shown by the convergence of the curves in Fig. 3 and 4 as P/D increases. As P/D structures increase, they provide greater incentive for higher protein levels. At high P/D structures, N price and wheat price have less influence relative to P/D structures on optimal N application levels. While optimal N rates increase significantly in response to increased P/D incentives in Fig. 3, only a modest increase is observed in resulting protein levels in Fig. 4. The convergence and ultimate crossing of the curves in Fig. 3 show the dominance of protein P/Ds when the reward for protein is high. At high P/Ds, net return is maximized in Stage 3 of yield production (negative marginal returns to N). The lines converge because the additional income from increased protein is greater than the reduction in income due to reduced yield (at the low wheat price) as N increases.

Tables 3 through 8 report maximum net returns and corresponding optimal N fertilization, protein, and yield levels for all six wheat and N price combinations vs. the two combinations shown in Fig. 3 and 4. Each line in each table reports the optimal N rate and resulting protein (g kg^{-1}) and yield (Mg ha^{-1}) that maximize net return at that P/D structure. For example, in Table 3, at a high wheat price of $191.10 Mg^{-1}, low N price of $0.49 kg^{-1}, and a P/D structure of $0.37 Mg^{-1} premium per 2.5 g kg^{-1} protein above 140 g kg^{-1} and $1.10 Mg^{-1} discount per 2.5 g kg^{-1} protein below 140 g kg^{-1}, net return is maximized at $681.27 ha^{-1} by fertilizing at 151 kg ha^{-1} N, with optimal protein of 137.7 g kg^{-1} and yield of 3.973 Mg ha^{-1}. Comparisons between the tables show changes in optimal N fertilization and maximum net return for different wheat price and N price combinations. Comparisons within tables reveal changes in N fertilization and maximum net return for different P/D structures.

All optimal N, protein, and yield levels in Tables 3 through 8 were within the data range of the field data. The patterns of optimal fertilization conformed to expected patterns of economic response. For example, within any wheat and N price combination, increasing P/D incentives for protein increases optimal N. Specifically in Table 6, moving from a $0.37/$1.10 Mg^{-1} P/D structure to a $1.47/$2.20 Mg^{-1} P/D structure results in an increase in optimal N by 12 kg ha^{-1}. With larger P/D, net return is maximized at higher protein levels to avoid the larger price discounts.

Increasing P/D structures from $0.37/$1.10 Mg^{-1} to $4.41/$7.35 Mg^{-1} increases maximum net return by $7.67 to $12.68 ha^{-1} at a low price of N and by $0.52 to $3.23 ha^{-1} at a high price of N. Maximum net return decreases slightly from the lowest P/D of $0.37/$1.10 Mg^{-1} to the next lowest of $1.47/$2.20 Mg^{-1} and then incrementally increases to the highest P/D structure. This dip is due to the greater magnitude of discounts compared with

Table 4. Optimal N fertilization rates and resulting net returns (NR), grain protein, and yield by varying protein premiums and discounts for conventional tillage hard red spring wheat under the following price conditions: intermediate-price wheat and low-price N.

N price = $0.49 kg^{-1}			Wheat price = $165.38 Mg^{-1}		
Premium	Discount	Optimal	Maximum	Optimal	Optimal
—— $ Mg^{-1} ——		N, kg ha^{-1}	NR, $ ha^{-1}	protein, g kg^{-1}	yield, Mg ha^{-1}
$0.37	$1.10	151	$579.08	137.7	3.973
$1.47	$2.20	161	$577.44	139.9	3.970
$2.20	$3.31	164	$577.57	140.6	3.966
$2.94	$4.41	172	$579.36	142.4	3.946
$4.41	$7.35	187	$588.94	145.7	3.879

Table 6. Optimal N fertilization rates and resulting net returns (NR), grain protein, and yield by varying protein premiums and discounts for conventional tillage hard red spring wheat under the following price conditions: high-price wheat and high-price N.

N price = $0.71 kg^{-1}			Wheat price = $191.10 Mg^{-1}		
Premium	Discount	Optimal	Maximum	Optimal	Optimal
—— $ Mg^{-1} ——		N, kg ha^{-1}	NR, $ ha^{-1}	protein, g kg^{-1}	yield, Mg ha^{-1}
$0.37	$1.10	144	$648.71	136.2	3.965
$1.47	$2.20	156	$644.51	138.8	3.974
$2.20	$3.31	162	$643.95	140.2	3.969
$2.94	$4.41	164	$644.19	140.6	3.966
$4.41	$7.35	178	$649.19	143.7	3.924

Table 7. Optimal N fertilization rates and resulting net returns (NR), grain protein, and yield by varying protein premiums and discounts for conventional tillage hard red spring wheat under the following price conditions: intermediate-price wheat and high-price N.

N price = $0.71 kg^{-1}			Wheat price = $165.38 Mg^{-1}		
Premium	Discount	Optimal	Maximum	Optimal	Optimal
—— $ Mg^{-1} ——		N, kg ha^{-1}	NR, $ ha^{-1}	protein, g kg^{-1}	yield, Mg ha^{-1}
$0.37	$1.10	143	$546.74	135.9	3.963
$1.47	$2.20	156	$542.30	138.8	3.974
$2.20	$3.31	162	$541.87	140.2	3.969
$2.94	$4.41	165	$542.21	140.8	3.964
$4.41	$7.35	180	$548.40	144.2	3.915

premiums and the discontinuous affect this has on the net return function.

Decreasing wheat price given a low N price (Tables 3 vs. 5) results in little change in optimal N levels at low P/Ds but increases N at higher P/Ds. This occurs because at low wheat prices and high P/Ds, the increase in net return from higher protein offsets the relatively small decrease in net return from fertilizing beyond maximum yield. Decreasing wheat prices given a high N price (Tables 6 vs. 8) also increases N at higher P/Ds. However, the increase in N is smaller due to the higher cost of N.

As expected, increasing N price at all wheat prices (Tables 3 vs. 6, 4 vs. 7, and 5 vs. 8) always decreases optimal N levels and resulting protein levels at both low and high P/Ds. This also reduces net returns in each scenario. Optimal yield varied little with changes in N or wheat prices holding P/Ds constant. Not surprisingly, wheat price is the dominant factor in changing net returns. Decreasing wheat prices from $191.10 Mg^{-1} to $139.65 Mg^{-1} while holding N constant (Tables 3–5) reduces net returns by $204 ha^{-1} at low P/Ds and $200 ha^{-1} at high P/Ds. Increasing N prices from $0.49 kg^{-1} to $0.71 kg^{-1} (Tables 3 vs. 6, 4 vs. 7, and 5 vs. 8) reduces net returns $33 to $39 ha^{-1}.

As expected, the attractive combination of a high wheat price of $191.10 Mg^{-1} combined with a low N price of $0.49 kg^{-1} resulted in the highest dollar-per-hectare net return within each of the respective P/D structures. Reducing the price of wheat while maintaining a low N price (Tables 4 and 5) caused little change in optimal N applied at lower P/D structures, but optimal N levels increased at higher P/D structures. Optimal protein levels increased slightly, and optimal yield levels decreased in each respective P/D structure at lower wheat prices. This reflects the increased value of protein and decreased value of yield as P/Ds increase and wheat price decreases.

Table 8. Optimal N fertilization rates and resulting net returns (NR), grain protein, and yield by varying protein premiums and discounts for conventional tillage hard red spring wheat under the following price conditions: low-price wheat and high-price N.

N price = $0.71 kg^{-1}			Wheat price = $139.65 Mg^{-1}		
Premium	Discount	Optimal	Maximum	Optimal	Optimal
—— $ Mg^{-1} ——		N, kg ha^{-1}	NR, $ ha^{-1}	protein, g kg^{-1}	yield, Mg ha^{-1}
$0.37	$1.10	141	$444.82	135.5	3.958
$1.47	$2.20	157	$440.07	139.0	3.973
$2.20	$3.31	162	$439.75	140.2	3.969
$2.94	$4.41	167	$440.29	141.3	3.960
$4.41	$7.35	185	$448.05	145.3	3.890

CONCLUSIONS

The objective of this research was to determine economically optimal N fertilization levels of HRSW for various wheat prices, N prices, and protein P/D structures based on yield and protein response to applied N for southeastern Washington data. Statistical relationships of grain protein and yield response to N fertilization were estimated. Estimated production functions for protein and yield were combined with price and protein P/D expectations to calculate net return–maximizing N rates.

Decreasing wheat price given a low N price resulted in little change in optimal N levels at low P/Ds but increased N at higher P/Ds as more net return could be made by fertilizing to increase protein. Increasing N price at all wheat prices always decreased optimal N levels and resulting protein levels at both low and high P/D structures. At low P/Ds, maximum net return was achieved by fertilizing for slightly less than 140 g kg^{-1} protein for both high and low N prices. Differences in net return between high and low P/D structures were small compared with differences induced by changes in wheat price or N price.

While exact results are specific to the soils and climate of the southeastern Washington experiment that provided the data for this analysis, the general directions of response to P/D structures, wheat prices, and N prices are likely to be similar elsewhere. This approach could be adapted to other regions as necessary data are collected to estimate local yield and protein response relationships to N. High levels of residual soil N can increase grain protein content in HRSW (Huggins, 1991). With more complete data on spring soil conditions, future research could include the yield and protein effects of varying residual soil N levels and preplant soil moisture levels. If response data over several years of representative weather were available, risk management analysis for alternative N fertilization strategies could be developed.

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