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

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Selected Paper prepared for presentation at the Western Agricultural Economics Association Annual Meeting, Denver, Colorado, July 15, 2003

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ABSTRACT

This analysis determines profit maximizing N fertilization levels of hard red spring wheat (HRSW) for various wheat prices, N prices, and protein-based HRSW price premium/discount (P/D) structures for south eastern Washington data. Fertilizer response data consisting of rates of N fertilization (lb/ac), grain yield (bu/ac), and grain protein (%) were used to statistically estimate regression relationships that predicted yield and protein in response to N. 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 14% expected protein. These results indicate that it is not always profitable to use "14% protein" as an N fertilization goal.

Abbreviations: CT, conventional tillage; HRSW, hard red spring wheat; HRWW, hard red winter wheat; N, nitrogen; NO_3, nitrate; NT, No Tillage; P/D, premium/discount; SWSW, soft white spring wheat; SWW, soft white wheat.

INTRODUCTION

Production of HRSW by dryland farmers in the Pacific Northwest has increased in recent years, possibly due to low prices for soft white wheat (SWW) relative to production costs. HRSW has maintained a varying price advantage over SWW in recent years (Janosky, USDA). Variety trials near Pullman WA, from 1997 to 2001 show that HRSW yield has averaged 3 bu/ac less than Soft White Spring Wheat (Burns, et al.). However recent trends with newer varieties show HRSW yields gaining on SWSW.

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, estimated that annual spring grain cropping of all current dryland fallow would reduce concentrations of suspended dust particles 10 micrometers 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 reduces the time period that the soil is unprotected from wind erosion (Papendick). However, Young, et al. report that continuous no-till 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 SWW, is influenced by protein concentration (%). Premiums ($/bu) are added to the base wheat price (reported at 14% protein) for each 0.25% above 14% protein and discounts ($/bu) subtracted from the base price for each 0.25% below 14% 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). Note that premiums vary greatly from $0.01/bu to $0.13/bu and discounts from $0.03/bu to $0.23/bu over this 10-year 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 effecting 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 pre-plant soil moisture and pre-plant 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 (HRWW) 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 nitrate (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 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 is dependent on the amount of water available for growth (Clarke et al., Rasmussen and Rohde, Terman et al., Whitfield and Smith). If water and other factors of growth are sufficient the first effect of applied nitrogen 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.).

Economic studies have derived profit maximizing input rates for other crops when inputs affect both yield and quality. Van Tassel et al. derived profit maximizing nitrogen application rates for sugar beet production that maximized profit considering root yield, sucrose content, and fertilizer cost. Profit was computed as gross revenue (sucrose-dependent price of sugar beets 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. estimated the profit maximizing nitrogen 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. on HRWW concluded that at moderate protein premiums of $0.03 per 0.25% above 12%, 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. 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 south eastern 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.

MATERIALS AND METHODS

Overview of Analysis

HRSW field experiment data consisting of rates of N fertilization (lb/ac), grain yield (bu/ac), and grain protein (%) 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 ($/ac) for the study region were found for thirty 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 growing seasons, 1987 and 1989. The sites were near Pullman, WA (21.5 in average annual precipitation). Table 2 reports average yield and protein by N application level and year for the data set. Nitrogen rates in the 1987 experiment were 0, 50, 100 and 150 lb/ac and in the 1989 experiment 0, 80, 120, 160, and 200 lb/ac (Huggins).

HRSW was grown under rain fed conditions in both no-till (NT) and conventional tillage (CT) regimes, following winter wheat in both years. 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). HRSW was seeded at 75.9 lb/ac on 10 April 1987 and at 84.8 lb/ac on 18 April, 1989 (Huggins).

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 ten years of historical Port of Portland price data. Premiums and discounts are in \$/bu per 0.25% above or below 14% protein. The HRSW prices were reported by USDA at Portland, Oregon. To convert these to southeastern Washington farm gate prices, they are reduced by \$0.40/bu 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).

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 Vaughn et al, (1990) the response function for yield was expected to be quadratic with a non-zero intercept and declining marginal productivity. 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.).

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 (\$/ac) function conditional on expected, grain price, N price, and P/D structure. Iterative use of a spreadsheet identified the N rate which 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 equations (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

$$Y = \underset{(18.73)}{27.71579} + \underset{(15.11)}{0.4573499}N - \underset{(-11.04)}{0.0016587013}N^2 - \underset{(-5.17)}{6.54453}T; \qquad \text{Adj. } R^2 = 0.63$$

2. Grain Protein

$$P = \underset{(41.43)}{10.41328} + \underset{(13.24)}{0.02493}N + \underset{(3.01)}{0.749}T; \qquad \text{Adj. } R^2 = 0.46$$

3. Net Returns Function

$$NR = (Pw*Y) - Pn*N + [((P - 14\%)/0.25\%) * (Prem.\text{ or } Disc.) * Y]$$

where

Y =	Grain Yield (bu/ac)
P =	Grain Protein (%)
N =	Pre-Plant Applied N (lb/ac)
T =	Binary Variable for Tillage (0 = Conventional Tillage, 1 = No-Tillage)
NR =	Returns above N costs ($/ac)
Prem. =	$/bu for each 0.25% above 14% Protein
Disc. =	$/bu for each 0.25% below 14% Protein

Pw = Price of HRSW ($/Bu)

Pn = Price N fertilizer ($/lb)

The relatively high *t*-statistics of all the regression coefficients confirm that applied N has a statistically significant impact upon 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 versus 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 (Figure 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 (Figure 1) 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 6.5 bu/ac below CT and expected protein concentrations 0.749% 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 conventional tillage. The general patterns of the results were the same for NT; however, 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 Figure 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 14% protein threshold is reached. Inadequate fertilization resulting in protein below the threshold impose a smaller NR penalty with low P/D's 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 to 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 14% protein for both high and low N prices (Figure 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 Figures 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 Figure 3, only a modest increase is observed in resulting protein levels in Figure 4. The convergence and ultimate crossing of the curves in Figure 3 show the dominance of protein P/D's when the reward for protein is high. At high P/D's net return is maximized in stage three 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 3-8 report maximum net returns, and corresponding optimal N fertilization, protein, and yield levels for all six wheat and N price combinations versus the two combinations shown in Figures 3 and 4. Each line in each table reports the optimal N rate and resulting, protein (%), and yield (bu/ac) that results in maximum net return at that P/D structure. For example in Table 3, at a high wheat price of $5.20/bu , low N price of $0.22/lb, and a P/D structure of $0.01/bu premium per 0.25% protein above 14% and $0.03/bu discount per 0.25% protein below 14%, net return is maximized at $276.54/ac by fertilizing at 135 lb/ac of N, with optimal protein of 13.8 % and yield of 59.2 bu/ac. 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 3-8 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 $0.01/$0.03 /bu P/D structure to a $0.04/$0.06 /bu P/D structure results in an increase in optimal N by 10 lb/ac. With larger P/D, net return is maximized at higher protein levels to avoid the larger price discounts.

Increasing P/D structures from $0.01/$0.03 /bu to $0.12/$0.20 /bu increases maximum net return by $3.19 to $5.24 /ac at a low price of N and by $0.27 to $1.41/ac at a high price of N. In all price scenarios maximum net return decreases slightly from the lowest P/D of $0.01/$0.03 /bu to the next lowest of $0.01/$0.03 /bu then incrementally increases to the highest P/D structure. This dip is due to the greater magnitude of discounts compared to premiums and the discontinuous affect this has on the net return function.

Decreasing wheat price given a low N price (Tables 3 versus 5) results in little change in optimal N levels at low P/D's, but increases N at higher P/D's. This occurs because at low wheat prices and high P/D's 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 versus 8) also increases N at higher P/D's. 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 versus 6; 4 versus 7; 5 versus 8) always decreases optimal N levels and resulting protein levels at both low and high P/D's. This also reduces net returns in each scenario. Optimal yield varied little with changes in N or wheat prices holding P/D's constant. Not surprisingly, wheat price is the dominant factor in changing net returns. Decreasing wheat prices from $5.20/bu to $3.80/bu while holding N constant (Tables 3 to 5) reduces net returns by $83/ac at low P/D's and $81/ac at high P/D's. Increasing N prices from $0.22/lb to $0.32/lb (Tables 3 versus 6, 4 versus 7, 5 versus 8) reduces net returns $13 to $17/ac.

As expected the attractive combination of a high wheat price of $5.20/bu combined with a low N price of $0.22/lb resulted in the highest $/ac 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/D's increase and wheat price decreases.

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 discount/premium 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/D's, but increased N at higher P/D's 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/D's maximum net return was achieved by fertilizing for slightly less than 14% protein for both high and low N prices. Differences in net return between high and low P/D structures were small compared to 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 premium/discount structures, wheat prices, and nitrogen 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 hard red spring wheat (Huggins). With more complete data on spring soil conditions, future research could include the yield and protein effects of varying residual soil N levels and pre-plant 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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Table 1. Annual average hard red spring wheat prices with corresponding protein premiums and discounts reported in $/bu per 0.25% above or below 14% protein.

Production Year	Price (14%) $ / bu	Discount $ / bu	Premium $ / bu
1991-1992	$4.26	$0.03	$0.01
1992-1993	$4.49	$0.10	$0.06
1993-1994	$5.51	$0.23	$0.13
1994-1995	$4.73	$0.09	$0.06
1995-1996	$6.15	$0.07	$0.05
1996-1997	$5.41	$0.05	$0.04
1997-1998	$4.70	$0.07	$0.05
1998-1999	$4.21	$0.06	$0.04
1999-2000	$4.02	$0.09	$0.06
2000-2001	$4.11	$0.07	$0.04

Source: USDA. Grain Market News. Port of Portland, OR prices, 2001.

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

Year	Nitrogen lb/ac	Yield Mg ha-1 bu/ac	Protein %
1987	0.0	29.5	10.77
	50.0	52.7	10.04
	100.0	69.0	11.17
	150.0	61.8	13.00
1989	0.0	21.7	13.03
	80.4	46.3	12.90
	119.7	50.0	14.64
	159.8	49.3	15.95
	200.0	50.3	16.91

Tables 3-8. Optimal Nitrogen Fertilization Rates and Resulting Net Returns (NR) Grain Protein and Yield, By Varying Wheat Prices, Protein Premiums and Discounts, and Nitrogen Input Prices for Conventional Tillage Hard Red Spring Wheat.

Table 3. High Price Wheat, Low Price N

N Price $/lb = $0.22			Wheat Price $/bu (14% Pro) = $5.20		
Prem. $/bu	Disc. $/bu	Optimal N lb/ac	Maximum NR $/ac	Optimal Protein %	Optimal Yield bu/ac
$0.01	$0.03	134.8	*$276.54*	13.77	59.2
$0.04	$0.06	143.8	*$275.87*	13.99	59.2
$0.06	$0.09	145.6	*$275.90*	14.04	59.1
$0.08	$0.12	151.8	*$276.45*	14.19	58.9
$0.12	$0.20	163.4	*$279.73*	14.48	58.1

Table 6. High Price Wheat, High Price N

N Price $/lb = $0.32			Wheat Price $/bu (14% Pro) = $5.20		
Prem. $/bu	Disc. $/bu	Optimal N lb/ac	Maximum NR $/ac	Optimal Protein %	Optimal Yield bu/ac
$0.01	$0.03	128.6	*$263.31*	13.62	59.1
$0.04	$0.06	139.3	*$261.63*	13.88	59.2
$0.06	$0.09	144.7	*$261.42*	14.02	59.1
$0.08	$0.12	146.5	*$261.53*	14.06	59.1
$0.12	$0.20	159.0	*$263.58*	14.37	58.5

Table 4. Intermediate Price Wheat, Low Price N

N Price $/lb = $0.22			Wheat Price $/bu (14% Pro) = $4.50		
Prem. $/bu	Disc. $/bu	Optimal N lb/ac	Maximum NR $/ac	Optimal Protein %	Optimal Yield bu/ac
$0.01	$0.03	134.8	*$235.11*	13.77	59.2
$0.04	$0.06	143.8	*$234.46*	13.99	59.2
$0.06	$0.09	146.5	*$234.53*	14.06	59.1
$0.08	$0.12	153.6	*$235.27*	14.24	58.8
$0.12	$0.20	167.0	*$239.19*	14.57	57.8

Table 7. Intermediate Price Wheat, High Price N

N Price $/lb = $0.32			Wheat Price $/bu (14% Pro) = $4.50		
Prem. $/bu	Disc. $/bu	Optimal N lb/ac	Maximum NR $/ac	Optimal Protein %	Optimal Yield bu/ac
$0.01	$0.03	127.7	*$221.96*	13.59	59.0
$0.04	$0.06	139.3	*$220.19*	13.88	59.2
$0.06	$0.09	144.7	*$220.03*	14.02	59.1
$0.08	$0.12	147.3	*$220.17*	14.08	59.1
$0.12	$0.20	160.7	*$222.71*	14.41	58.3

Table 5. Low Price Wheat, Low Price N

N Price $/lb = $0.22			Wheat Price $/bu (14% Pro) = $3.80		
Prem. $/bu	Disc. $/bu	Optimal N lb/ac	Maximum NR $/ac	Optimal Protein %	Optimal Yield bu/ac
$0.01	$0.03	134.0	*$193.67*	13.75	59.2
$0.04	$0.06	143.8	*$193.06*	13.99	59.2
$0.06	$0.09	147.3	*$193.18*	14.08	59.1
$0.08	$0.12	156.3	*$194.18*	14.30	58.6
$0.12	$0.20	171.5	*$198.91*	14.68	57.3

Table 8. Low Price Wheat, High Price N

N Price $/lb = $0.32			Wheat Price $/bu (14% Pro) = $3.80		
Prem. $/bu	Disc. $/bu	Optimal N lb/ac	Maximum NR $/ac	Optimal Protein %	Optimal Yield bu/ac
$0.01	$0.03	125.9	*$180.64*	13.55	59.0
$0.04	$0.06	140.2	*$178.75*	13.90	59.2
$0.06	$0.09	144.7	*$178.63*	14.02	59.1
$0.08	$0.12	149.1	*$178.86*	14.13	59.0
$0.12	$0.20	165.2	*$182.05*	14.53	58.0

Fig. 1. Grain Yield and Protein Response to Applied Nitrogen per Equation (1) and (2) Respectively.

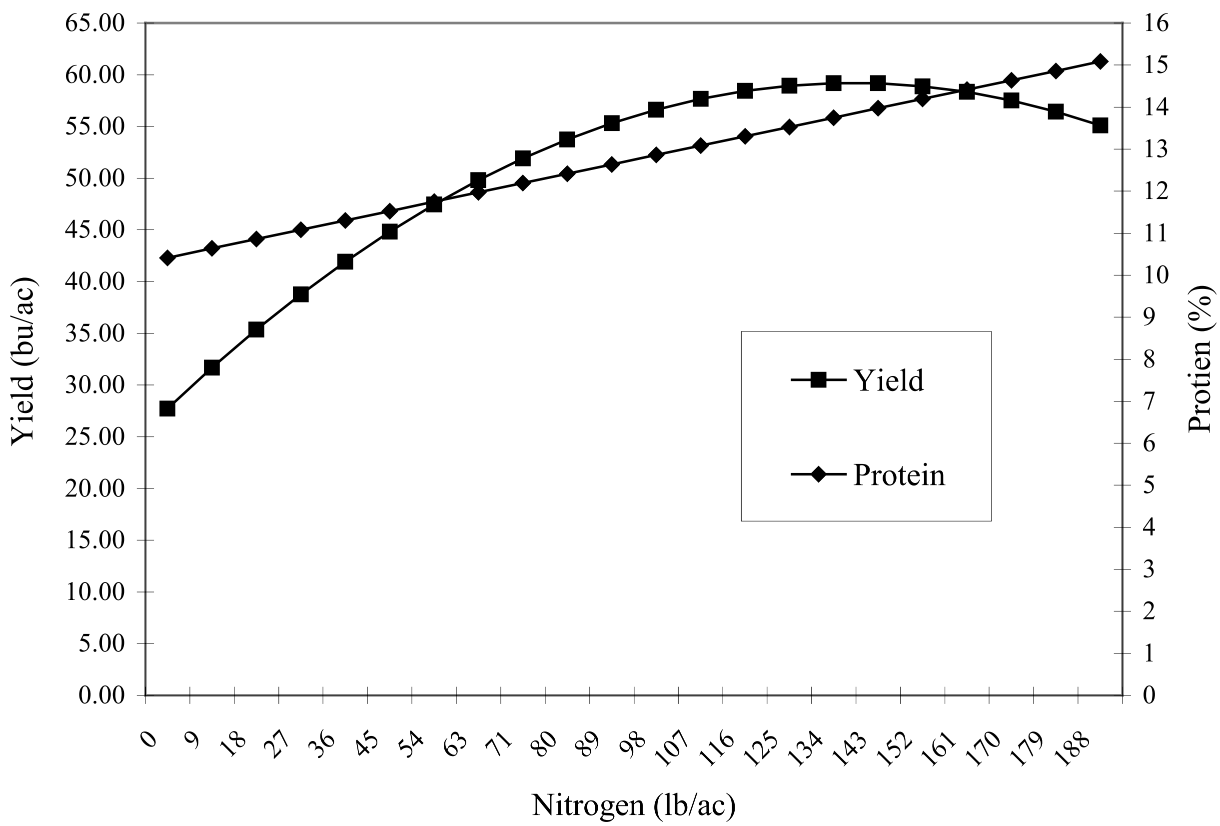

Fig. 2. Net Returns Response to N Fertilization for High Wheat Price/Low N Price and Low Wheat Price/High N Price combinations.

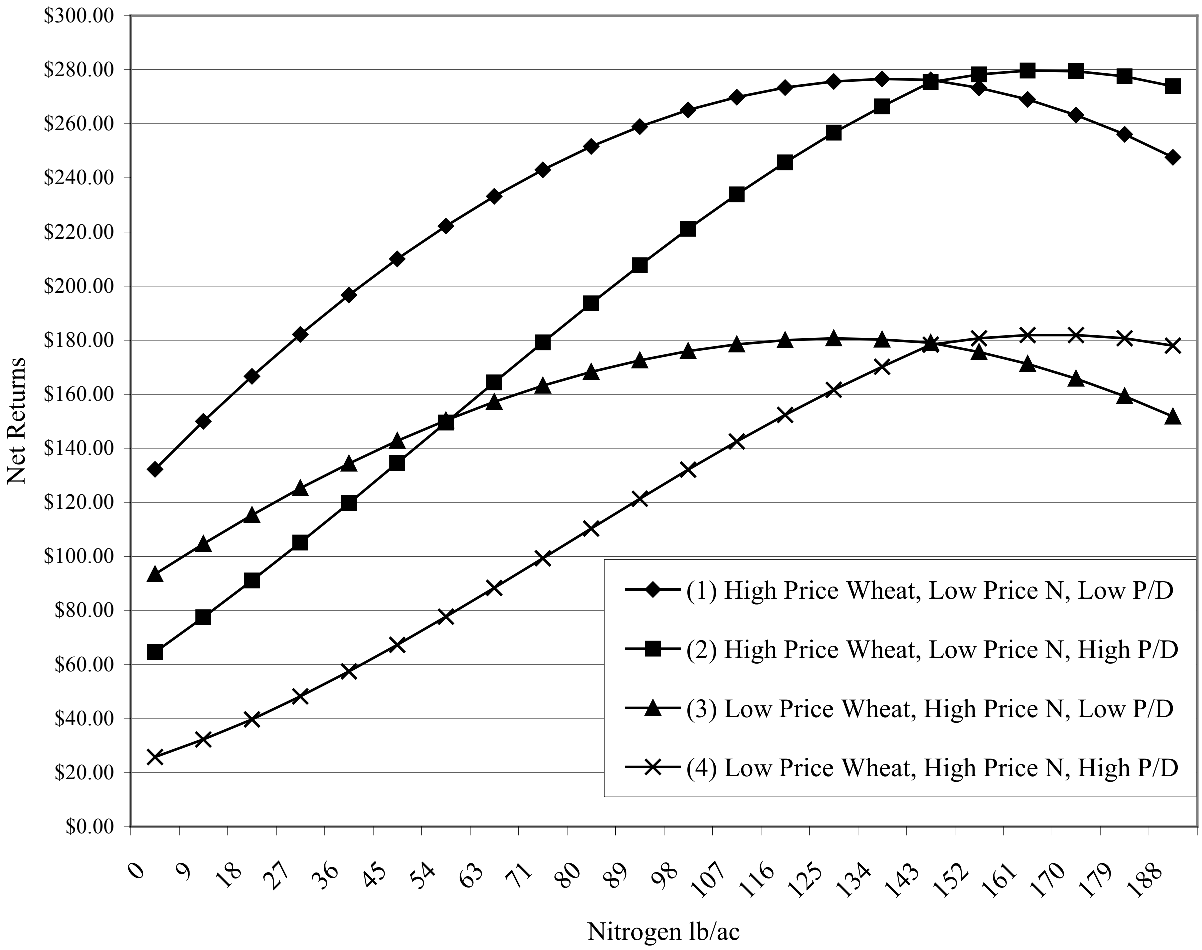

Fig. 3. Economically Optimal Nitrogen Levels in Conventional Tillage Hard Red Spring Wheat for Varying Premium and Discount (P/D) Price Structures.

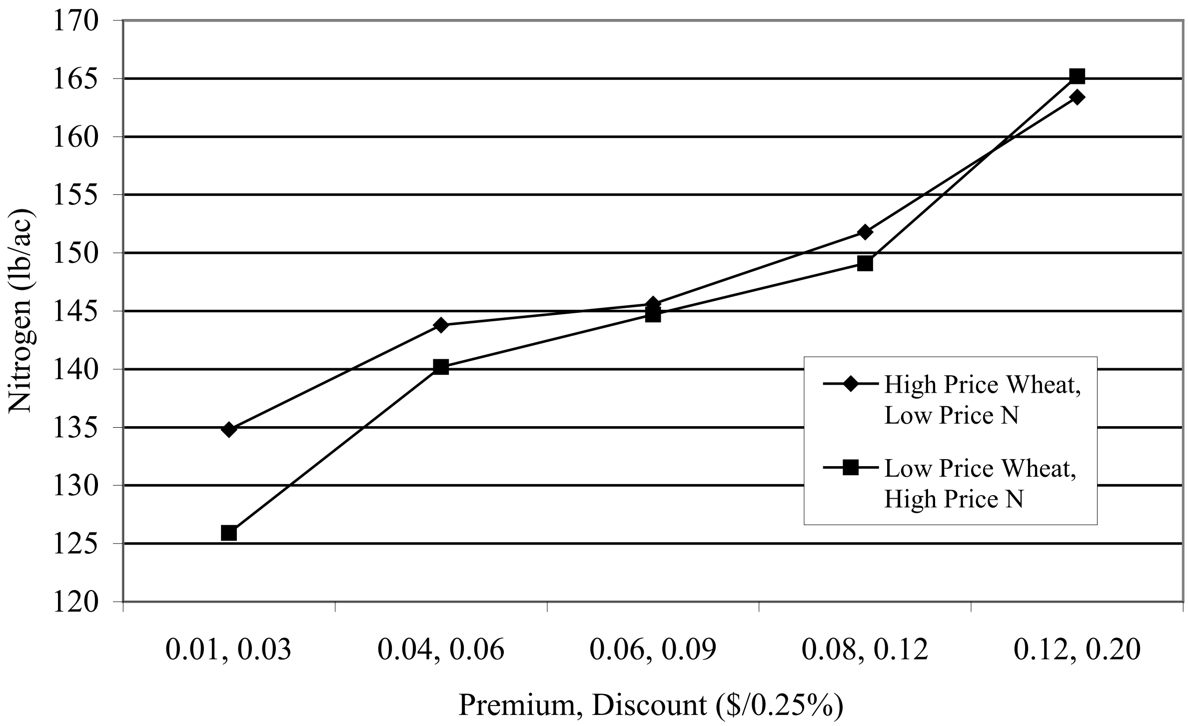

Fig. 4. Economically Optimal Protein Levels in Conventional Tillage Hard Red Spring Wheat for Varying Premium and Discount (P/D) Price Structures.