Modeling Economic Optimum Nitrogen Rates for Winter Wheat When Inputs Affect Yield and Output-Price

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Abstract

An empirical model to examine economically optimal nitrogen fertilizer rates for winter wheat when nitrogen affects crop yield and crop price is presented. The results show that the ex post estimated economically optimal nitrogen rate for one of the two analyzed experimental sites was 33-43 kg ha^{-1} higher when the relationship between the protein concentration and the price is considered compared to the situation when constant wheat price was assumed. Not considering the wheat price-protein relationship resulted in an economic loss of 135-137 € ha^{-1}. Therefore, negative economic consequences of under-fertilizing seem to rise when quality and its effect on output price is considered on such fields.

Key Words: *nitrogen response functions, protein response function, valuing grain protein concentration, winter wheat, economic optimum nitrogen rates*

Introduction

Crop quality (e.g. the protein concentration in wheat) has a great impact on the achieved prices of commodities and sometimes it is even a prerequisite for market access. Therefore, producers are aware of the importance of crop quality for most of their products.

Only few studies investigated crop quality response to applied nitrogen fertilizer and its economic consequences. Baker et al. (2004) determined profit-maximizing N fertilizer levels for hard red spring wheat (HRSW) for various wheat prices, nitrogen prices, and protein based price premium/discount structures. They used fertilizer response data for HRSW to estimate nitrogen and protein response functions, and found that high premium/discount structures lead to economically optimal N-rates for HRSW that are often higher than yield maximizing N-rates. In addition, they found that fertilizing to achieve 14% protein concentration was not always the profit maximizing strategy. In another study, Norton et al. (1997) estimated the economically optimal nitrogen rates of grass hay considering yield and protein concentration. Clark et al. (1991) included hay quality when deriving economically optimal fertilization rates for subirrigated meadow hay production. Van Tassell et al. (1996) calculated economically optimal nitrogen rates for sugar beets considering root yield and sucrose content, where the latter has an impact on the output price.

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The aim of this paper is to provide ex post estimates of economically optimal nitrogen rates for winter wheat when nitrogen affects both crop yield and crop price. Furthermore, the analysis should evaluate economic consequence of fertilizing without considering the protein response to nitrogen (i.e. protein concentration). This evaluation is important because mostly only the yield response to nitrogen is used to estimate economically optimal nitrogen rates without considering the price-protein relationship. These estimates may lead, under certain conditions, to misleading conclusions in terms of economically optimal nitrogen rates. The paper should show under which conditions this could be the case. Since the site-specific protein response to nitrogen can be gathered with near infrared sensors mounted in combine harvesters the results can be used to improve nitrogen recommendations. In addition the results may help to understand why farmers often tend to over fertilize.

Data

The grain yield and protein response functions to applied nitrogen fertilizer used for this study were obtained from N-rate field trials, which were conducted on 2 locations in South Germany in 2000, 2001 and 2002 (see Hege and Offenberger, 2002). Table 1 provides the climate and soil characteristics of the two experimental sites in Betzdenorf and Wolfsdorf. As it can be seen, the experimental site in Betzendorf is slightly less favourable in terms of precipitation, average temperature and soil value. It is important to note that on both experimental sites the production of high quality wheat is feasible. At each location the response of crop yield and protein concentration to nitrogen fertilization was tested. The experimental design includes six N treatments with three replicates for each treatment. Nitrogen supply varied within the range of 0 to 200 kg N ha^{-1}. Yield was measured with a plot combine. The harvested plot size was 10 m². The nitrogen in kernel was determined according to Kjeldahl. The average yield and protein concentration by nitrogen level for the two trial sites over three years are listed in Table 2 (see Hege and Offenberger, 2002).

Table 1. Characteristics of the two experimental sites

location	precipitation	average temperature	altitude	soil type	soil value index
	mm a^{-1}	°C	m		
Betzendorf	643	8.3	372	brown earth	55
Wolfsdorf	665	8.5	270	brown earth	60

Source: Hege and Offenberger (2002)

As mentioned before, the price of winter wheat depends on various quality attributes, especially the grain protein concentration. Generally, there are fixed prices within certain intervals of protein concentration. When a threshold protein concentration is reached, a higher price is paid. Therefore the price-protein relationship looks like a step-function. Nitrogen fertilizer is the key management factor affecting the protein concentration during the vegetation period. Therefore we don’t account in the presented analysis for the Falling Number and the Thousand Grain Weight relationship to the wheat price since we want to optimize nitrogen management.

The price-protein relationship for different quality levels of wheat used for our calculations, according to the Bavarian wheat market in 2000/01 and 2004/05, is presented in Table 3. The two years of price data we use show fairly different structures. While the prices in 2004/05 are about 15% lower compared to 2000/01 the quality incentive from quality wheat to elite wheat is only about the half. The nitrogen price for the presented calculations is assumed to be 0.81 € kg^{-1} according to the actual price situation all other to fertilizing related costs are assumed to be constant.

Table 2. Three year average (2000-2002) winter wheat yield and grain protein concentration by N level for Betzendorf and Wolfsdorf

Location	N	Yield	Proteinconcentration
	kg ha^{-1}	t ha^{-1}	%
Betzendorf	0	4.61	11.5
	40	5.19	11.6
	80	5.88	12.7
	120	6.23	14.8
	160	6.40	16.2
	200	6.23	17.3
Wolfsdorf	0	4.66	9.3
	40	6.01	8.8
	80	7.13	9.9
	120	7.77	11.7
	160	8.20	13.1
	200	8.50	14.2

Source: Hege and Offenberger (2002)

Nitrogen Budgeting when Nitrogen Affects Crop Price and Yield

Equations 1 and 2 show the regression models for yield and protein concentration response to applied nitrogen. Yield response to nitrogen is assumed to follow a quadratic regression model. Protein response to nitrogen is assumed to be linear (see Baker et al. 2004).

Yield Response Function to Nitrogen:

$$Y = a + bN + cN^2 \qquad (1)$$

where:

Y = grain yield (t ha^{-1})

a, b, c = coefficient of regression for the yield response function to nitrogen

N = N rate (kg ha^{-1})

Protein Response Function to Nitrogen:

$$P = \alpha + \beta \cdot N \tag{2}$$

where:
P = Protein Concentration (%)
α, β = coefficient of regression for the protein response function to nitrogen

Equation 3 reports the relationship between protein concentration and price of winter wheat (p_W), common for the wheat market in Germany. The price-protein-relationship depending on the protein response function to nitrogen P is given by (3):

$$p_w = \begin{pmatrix} "p_{Elite\ Wheat}" \ \ if\ P \geq 14.0\% \\ "p_{Quality\ Wheat}" \ if\ P \geq 13.5\% \\ "p_{Milling\ Wheat}" \ if\ P \geq 12.5\% \\ "p_{Feeding\ Wheat}" if\ P < 12.5\% \end{pmatrix} \text{ where } P = h(N) \tag{3}$$

Equation 4 integrates the equations 1, 2 and 3 into a net returns function.
Net Returns Function:

$$NR = p_w \cdot Y - p_N N \text{ where } p_w = g(P) \text{ and } Y = f(N) \tag{4}$$

where:
NR = Net Return (€ ha^{-1})
p_N = price of nitrogen fertilizer (€ kg^{-1})
p_W = price of winter wheat (€ t^{-1})

The optimization problem can be written as given by equation (5):

$$MaxNR = (g(h(N))) \cdot f(N) - p_N N \tag{5}$$

The objective is to maximize net returns by choosing the N-rate. Therefore $MaxNR$ shows economically optimal nitrogen rates considering yield and protein concentration response to nitrogen and the actual price-protein-relationships described in (3).

$MaxNR$ is being compared to $NR_{Pw(const.)}$ which is calculated using a constant product price for wheat and, ignoring the actual price-protein relationship. The nitrogen rate ($N_{NR_{Pw(const.)}}$) for $NR_{Pw(const.)}$ can be calculated by solving the first order condition of equation 4 for *N*, assuming a constant wheat price $p_{w(const.)}$, and setting it to zero:

$$\frac{\partial(NR)}{\partial(N)} = p_{w(const.)} \cdot \frac{\partial f(N)}{\partial(N)} - p_N = 0$$

$$\frac{\partial f(N)}{\partial(N)} = \frac{p_N}{p_{w(const.)}} \tag{6}$$

However, the actual wheat price for $NR_{Pw(const.)}$ depends on the protein concentration, which, in turn, is a function of the N-rate given by (3). Therefore, the actual net revenue achieved when a constant wheat price is assumed ($NR_{Pw(const.)}$) is calculated according to equation (7):

$$NR_{Pw(const.)} = (g(h(N_{NR_{Pw(const.)}}))) \cdot f(N_{NR_{Pw(const.)}}) - p_N N_{NR_{Pw(const.)}} \qquad (7)$$

If there is a nitrogen rate different from $N_{NR_{Pw(const.)}}$ that results in a higher net return, assuming a constant wheat price is not an optimal strategy, and the nitrogen rate should be adjusted. The optimal nitrogen rate in this case would satisfy equation (5).

The potential increase in net returns resulting from the N-rate adjustment reflects the importance of considering the relationship between nitrogen and wheat price in nitrogen recommendations for wheat. Since the protein-price relationship is a step function, the nitrogen-price relationship will also have „kinks“ where it is not differentiable. Thus, the optimization problem given in (5) will be solved numerically rather than setting the first derivative equal to zero. In this paper we will calculate the optimal nitrogen rate that maximizes net returns for two sites in Bavaria when protein-wheat price relationship is taken into account and compare it to the rate that assumes a constant wheat price.

Response Function Analysis

Estimated regression parameters and coefficient of determination R^2 (estimate of goodness of fit) for the quadratic nitrogen response functions and for the linear protein functions are presented for each trial site in Table 4. The R^2 is 0.99 for both yield response models; therefore the regression model provides a good fit to the observed data. The R^2 for the protein response functions are slightly lower but still both over 0.90 and therefore also shows a good fit to the measured protein data. The high t statistics (see Table 4) for all regression parameters indicate that nitrogen fertilizer has a statistically significant effect on the grain yield and grain protein concentration.

Figure 1 illustrates the estimated yield response functions to nitrogen for the two trial sites in Betzendorf and Wolfsdorf. While the intercepts for the two response functions are almost the same, the slopes of the functions are considerably different. As a consequence the two sites show a rather different yield response to nitrogen. The estimated protein functions for the trial sites are shown in Figure 1. The two protein response functions seem to be, unlike the yield response functions, almost parallel. Consequently, the protein response to an additional amount of nitrogen is almost the same in both sites. But, it is notable that the protein level in Betzendorf is quite high even at low nitrogen levels. Figure 1 illustrates that 14% protein concentration can be obtained with 100 kg N per hectare at the trial site in Betzendorf.

Economic Consequences of Ignoring Price-Protein Relationship when Economic Optimum N-Rates are estimated

Table 5 displays economically optimal nitrogen rates, the corresponding yields, protein concentration, wheat prices and net returns derived by two different optimisation strategies (“$MaxNR$” & “$NR_{Pw(const.)}$”) for each of the analysed sites (Betzendorf/Wolfsdorf) and for the two years of price data described in Table 3. In addition, it reports the differences in the economically optimal rates between the two optimisation strategies. Strategy (1) " $MaxNR$ " shows economically optimal nitrogen rates considering yield and protein concentration response to nitrogen and the actual price-protein-relationships. The economically optimal nitrogen rates for Strategy (2) " $NR_{Pw(const.)}$ " are calculated according to a constant product price for quality wheat of 121 € t^{-1} (2000/01) and 95 € t^{-1} (2004/05), ignoring the actual price-protein relationship. However, the actual wheat price for " $NR_{Pw(const.)}$ " depends on the protein concentration, which, in turn, is a function of the N-rate.

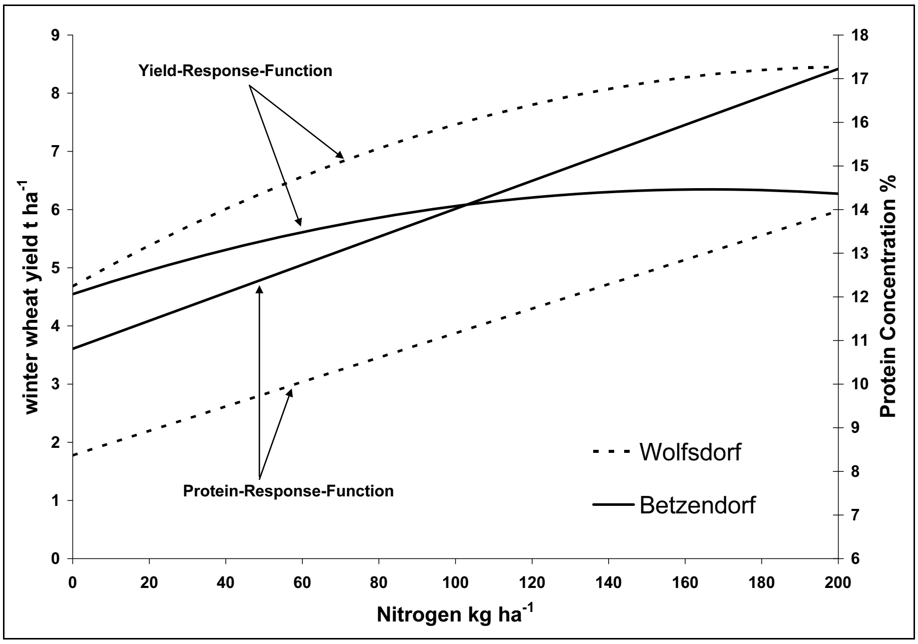

Figure 1. Estimated average (2000-2002) winter wheat yield and protein response functions to nitrogen

Table 3. Winter Wheat Quality Levels and corresponding Prices for the years 2000/01 and 2004/05

Quality Level		Assumed Minimum Protein Concentration	Price 2000/01*	Price 2004/05*
		%	€ t^{-1}	€ t^{-1}
Elite	Wheat	14,0	128	108
Quality	Wheat	13,5	121	95
Milling	Wheat	12,5	110	90
Feeding	Wheat	10,5	105	87

*Source: Reisenweber and Goldhofer (2006)

Table 4. Estimated regression parameters and R^2 for the averaged (2000-2002) winter wheat yield and protein response functions to nitrogen

Location	Yield-Response-Function				Protein-Response-Function		
	a	b	c	R^2	α	β	R^2
Betzendorf	4.547 (56.3)*	0.02164 (11.4)	-0.000065 (-7.1)	0.99	10.81 (26.5)	0.03207 (9.5)	0.96
Wolfsdorf	4.682 (72.0)	0.03674 (24.0)	-0.000089 (-12.2)	0.99	8.367 (16.5)	0.028 (6.7)	0.92

*Coefficient t statistics

Table 5. Economic optimum N-rates and the corresponding yield, protein concentration, wheat price and net returns for two locations (three year average) and two fertilization strategies

Location/Strategy	EONR*	Yield	Protein	Wheat Price	Net Return
	kg ha^{-1}	t ha^{-1}	%	€ t^{-1}	€ ha^{-1}
	Winter-Wheat-Price-Structure 2004/2005				
Betzendorf					
1. Max. NR	109	6,13	14,3	108	576
2. $NR_{Pw(const.)}$	100	6,06	14,0	108	576
Difference 1-2	9	0,07	0,3	0	0
Wolfsdorf					
1. Max. NR	201	8,46	14,0	108	754
2. $NR_{Pw(const.)}$	158	8,25	12,8	90	617
Difference 1-2	43	0,21	1,2	18	137
	Winter-Wheat-Price-Structure 2000/2001				
Betzendorf					
1. Max. NR	118	6,19	14,6	128	695
2. $NR_{Pw(const.)}$	115	6,17	14,5	128	695
Difference 1-2	3	0,02	0,1	0	0
Wolfsdorf					
1. Max. NR	201	8,46	14,0	128	916
2. $NR_{Pw(const.)}$	168	8,33	13,1	110	781
Difference 1-2	33	0,13	0,9	18	135

* EONR: Economic Optimum Nitrogen Rate

Table 5 shows the economically optimal N rate (EONR) for the trial site in Betzendorf. The EONR for the price data of 2004/05 are almost the same for both strategies and fairly low at 109 ($MaxNR$) and 100 kg N ha^{-1} ($NR_{Pw(const.)}$) with a difference of 9 kg N ha^{-1}. Therefore, the corresponding yields, protein concentrations, wheat prices and net returns are almost the same as well. These results are not surprising because, as it was mentioned before; high protein concentration can be reached with low nitrogen inputs on this trial site. Consequently, the economically optimal nitrogen rate is solely dependent on the yield response. Thus, under these circumstances it is not important to consider the site-specific-protein-response to nitrogen when calculating economically optimal nitrogen rates.

The situation in Wolfsdorf is rather different to that observed in Betzendorf. As it can be seen in Table 5, the EONR for the two optimization strategies differ about 43 kg N ha^{-1} for the assumed price data from 2004/05. Calculating the EONR for a constant quality wheat price and ignoring the actual protein response to nitrogen ($NR_{Pw(const.)}$) leads to an economically optimal rate of 158 kg N ha^{-1}. However, the protein concentration of 13.5% for quality wheat (95 € t^{-1}) could not be reached with this N-rate, the actual protein concentration is only 12.8% which means that the price will be the one paid for milling wheat (90 € t^{-1}). Considering instead the protein response to nitrogen and the corresponding price-protein-relationship would result in an economic optimum nitrogen rate of 201 kg N ha^{-1}, this N-rate leads to a protein concentration of 14% and a corresponding wheat price of 108 € t^{-1} and a net return of 754 € ha^{-1}, which is 137 € ha^{-1} higher compared to optimization strategy (2) where the actual protein response to nitrogen is not considered.

Therefore, two mayor aspects have to be highlighted for the trial site in Wolfsorf:

First, the N-rate calculated only considering yield response function to nitrogen and assuming a constant wheat price for quality wheat was not high enough to obtain the protein concentration needed to achieve the assumed wheat price. Second, even high quality wheat with a protein concentration of 14% and a corresponding wheat price of 108 € t^{-1} which is 13 € t^{-1} higher than the aimed price for quality wheat could be produced on his trial site if the N-rate was sufficiently high. Both aspects led to the enormous financial loss of 137 € ha^{-1} when assuming a specific quality level could be achieved without examining the actual protein response to nitrogen.

Although, the winter wheat price is fairly different in the year 2000/01 form the price in 2004/05 in terms of its absolute level and the quality premiums, the results of the comparisons of the two fertilization ("$MaxNR$" & "$NR_{Pw(const.)}$") strategies are almost the same. As the absolute price level in 2000/01 is higher than in 2004/05 the ENOR are in most cases somewhat higher as well. Furthermore, the results indicate that under the given price cost assumptions, at a three-year average, the most profitable option would be to produce premium wheat on both analysed sites.

To provide a graphical impression of the presented results the average net return functions are illustrated in Figure 2 for the assumed price regimes of 2004/05 for the two experimental sites at Betzendorf and Wolfsdorf. Both profit functions show clearly profit steps which are determined by the underlying nitrogen-protein and the protein-price relationship.

Conclusion

The results of this ex post analysis indicate that assuming a specific constant wheat price/quality level and ignoring the actual protein-response to nitrogen and the price-protein relationship can lead to three different situations regarding the two estimated economically optimum nitrogen rates (EONR):

(1) The EONR are almost the same when considering protein response to nitrogen compared to ignoring it. In that case there are no negative economic consequences if a farmer is assuming a constant wheat price. This situation can occur on sites where even with low nitrogen rates high protein concentrations can be gained, like it can be observed for the trial site in Betzendorf.

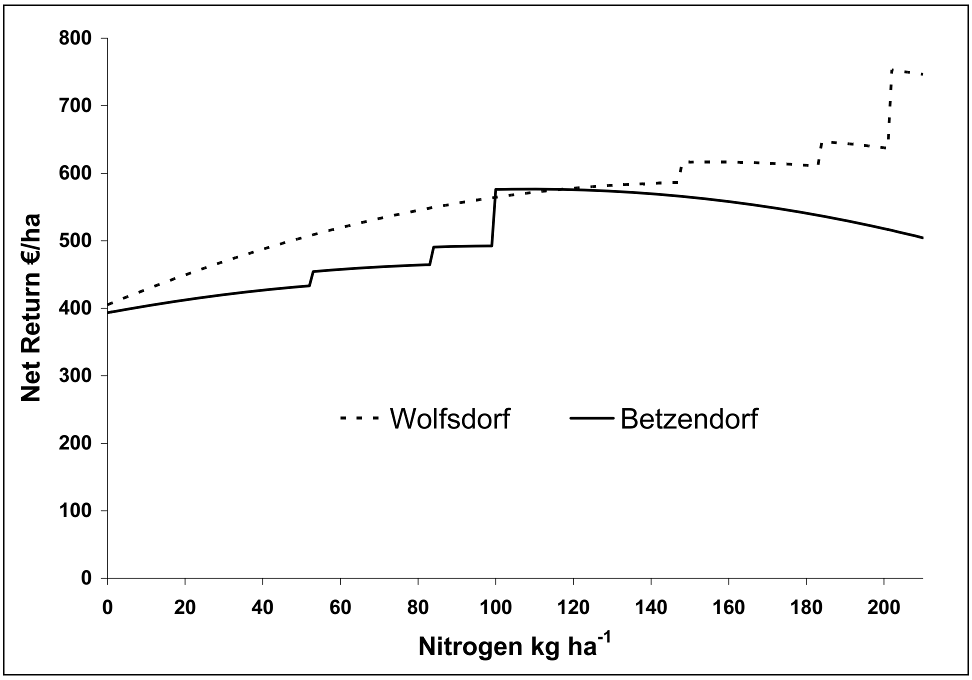

Figure 2. Average Net Return Function calculated for the price regimes of 2004/05 for the experimental sites in Wolfsdorf and Betzendorf

(2) The economically optimal nitrogen rates can be higher when considering protein response to nitrogen than when assuming a constant wheat price, as it is observed for the trial site in Wolfsdorf. This can be the case, when the field shows a rather high protein response to nitrogen but at an overall low starting level. Therefore, high rates are needed to achieve desired protein concentration. The economic consequence of assuming a constant wheat price can be that the achieved wheat price is lower than the expected price because the nitrogen rate is not high enough to obtain the protein concentration needed to achieve the assumed price. As a result, high losses in net returns to

nitrogen must be accepted when the actual protein response to nitrogen is not considered. Therefore, on such sites the economic consequences of too low N-rates can be significantly underestimated when a constant wheat price is assumed. This is also important to consider when calculating compensation payments, e.g. when farmers choose lower N-rates as they take part in agro-environmental programs.

(3) The third, but in this study not observed situation can be that nitrogen rates are higher when assuming a constant wheat price compared to the case when the price-protein relationship is taken into account. This situation could occur due to extremely low protein response to nitrogen caused by unfavourable weather conditions. In this case, only the lowest quality wheat would have been produced no matter how high the application rate was. As a result the assumed price would likely be too high for a particular site and the application rate would be higher than if the adequately low price was assumed. The economic consequences are in that case not as far-reaching as outlined in situation (2) since the producer is in this case faced only with wasted nitrogen fertilizer cost, resulting form over fertilizing. Unlike the previous case, there is no foregone price gain due to the incorrectly estimated N-rate.

Finally the results of this study show that the economically optimal nitrogen rates when quality aspects are taken into account can be significantly different from those when quality is not taken into account. In such cases the profit functions to nitrogen fertilizers is not as flat as for many other agricultural inputs, as described by Pannell (2006). These results seem to be relatively stable for different price-data. Therefore, in ex post estimation of optimal N-rates quality patterns should be included, especially when the price-quality dependency is strong, as it is the case for higher quality levels of winter wheat, summer barley or sugar beats. From the economic point of view the value of information about the site-specific protein response to nitrogen might be rather high if it can be implemented in site-specific or uniform nitrogen recommendations. As protein concentration can be measured during the harvest with near infrared sensors installed in the combine harvester (Taylor et al., 2005) the cost of information should not be too high in the future.

Also, the negative economic consequences of under-fertilizing seem to rise under certain circumstances when quality and its effect on output price is considered. This may be one of the reasons why farmers often tend to over-fertilize (Sheriff, 2005; Yadav et al., 1997). As neither the yield response function nor the protein response function to nitrogen is known at the time nitrogen fertilizer is applied, a more detailed long term risk analysis (with historical data) considering yield and protein response to nitrogen is needed to account for uncertainty and to show either high nitrogen rates are economically risk reducing or not.

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