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Economic analysis of site-specific wheat management with respect to grain quality and separation of the different quality fractions

Meyer-Aurich A.¹, Gandorfer M.², Weersink, A.³ and Wagner, P.⁴

¹ Leibniz-Institute for Agricultural Engineering, Department of Technology Assessment and Substance Flows, Potsdam, Germany

² Technische Universität München, Freising, Germany

³ University of Guelph, Guelph, Canada

⁴ Martin Luther Universität Halle, Halle, Germany

Abstract— The paper analyzes site-specific and uniform management options for wheat production with respect to grain quality. Besides site-specific fertilization the economic potential of segregation of different grain qualities is the subject of this paper. Yield and quality response to fertilizer were taken from field experiments in Germany to calculate site-specific response functions. The economic optima were calculated for uniform management (UM), complete separate management of the subfields (SM), site-specific fertilization (SSF) and grain segregation (GS) for different price structures according to different grain qualities. The results show that over all price structures, highest economic potential was found with SM or SSF compared to UM. However, these management practices require the possibility to separately manage subfields (SM) or specific fertilization equipment and fertilizer algorithms (SSM). GS did not have a higher economic potential than UM. However, if required grain qualities are not met for the whole field, GS can substantially reduce profit losses by separating part of the grains and selling them at higher prices. This may save the farmer more than 50 €ha⁻¹. In situations where higher grain qualities could only be obtained at the expense of yield penalties, premiums for higher grain qualities can create incentives for fertilizer rates beyond the yield maximizing rate. GS technologies may even boost this effect.

Keywords— site-specific nitrogen management, wheat quality, grain segregation.

I. INTRODUCTION

Despite the possibility to apply fertilizer more efficiently with site-specific management technologies, it has been shown that the advantages do not necessarily cover the costs of information gathering and the implemented technologies [4]. One reason for this can be seen in the flat profit function, which implies little economic potential in adjusting the economic optimum to the site-specific crop yield response [7]. Furthermore, it is difficult to predict optimal fertilizer applications ex ante, which seems to be an important factor for the success of site-specific

fertilization concepts [4]. However, the profitability of site-specific fertilization might be different when crop quality is affected by input use and payments are adjusted to crop quality.

The quality related price structure can create the incentive to separate the harvested grains into different fractions of specific qualities. This could be achieved through zone harvesting [9], separation in harvesters with specific online sensors [5] or separation at the farm [8]. To date only few studies have analysed the combined effect of site-specific fertilization on crop yield and crop quality [6]. In an economic analysis, Long et al. [2] found scant evidence of economic profitability for spring wheat production under site-specific management with the consideration of quality specific prices. No studies were found which modelled site-specific harvesting over a range of fertilizer levels with respect to N-response in yield and grain quality.

Since near infrared sensors provide the technical basis for the online measurement of grain protein content in combine harvesters, it seems feasible to manage the protein response to nitrogen more appropriately. Therefore, the aim of this study was to analyse the economic potential of site-specific management of wheat under different fertilizer management and harvest strategies with respect to grain quality.

II. THEORETICAL CONSIDERATIONS

Assuming nitrogen initially only affects yield and not quality, then the nitrogen application rate (N) that maximizes profit to a farmer is found by solving the following first order condition explicitly for nitrogen,

$$\frac{\partial F(N)}{\partial N} = P_N / P_Y \quad (1)$$

where $Y=F(N)$ is the production function ($F(N)$)

relating the application rate to the quantity of crop produced per unit of land (Y), and the prices of nitrogen and output are P_N and P_Y respectively. At the optimum, the marginal product of nitrogen is equal to the price ratio.

Now let us assume that nitrogen influences quality (Q) as well as yield through the response function $Q=Q(N)$ with $Q_N>0$ and $Q_{NN}<0$. The price of the crop now depends on its quality, $P_Y(Q)$ with higher prices resulting from increases in quality. The profit maximizing problem with quality and quantity considerations is

$$P_Y Y - P_N N = P_Y(Q(N))F(N) - P_N N \quad (2)$$

with the resulting first order condition

$$(\partial P_Y / \partial Q)(\partial Q / \partial N) * Y / P_Y + \partial F(N) / \partial N = P_N / P_Y \quad (3)$$

for maximal profit.

Since the first term in equation (3) is positive (higher N increases quality and higher quality increases price), the profit maximizing rate with quality consideration will be higher than if only quantity is considered. The equality in (3) will hold only if the marginal product of nitrogen (FN) is less than in equation (1). The profit maximizing rate could even be higher than the yield maximizing rate, which is where $FN=0$ provided that $(\partial P_Y / \partial Q)(\partial Q / \partial N) * Y = P_N$. In other words, the incremental benefit from a higher premium for a given yield is equal to the incremental cost of an additional unit of nitrogen generating the increased quality return.

The concepts are illustrated in Figure 1. The top panel shows the two technical relationships associated with nitrogen application. The first is a quadratic yield response function,

$$Y = \beta_0 + \beta_1 N + \beta_2 N^2 \quad (4)$$

and the other is a linear quality response function,

$$Q = \alpha_0 + \alpha_1 N. \quad (5)$$

The bottom panel gives the profit per unit of land from nitrogen application. The optimal nitrogen rate considering only yield is given by N_0 where the slope of the yield response function (or marginal product) is equal to the price ratio (P_N/P_Y) which is given by the dotted line. This nitrogen rate generates a maximum profit of π^Y_0 which is the peak of the profit function from alternative application rates assuming only yield is considered.

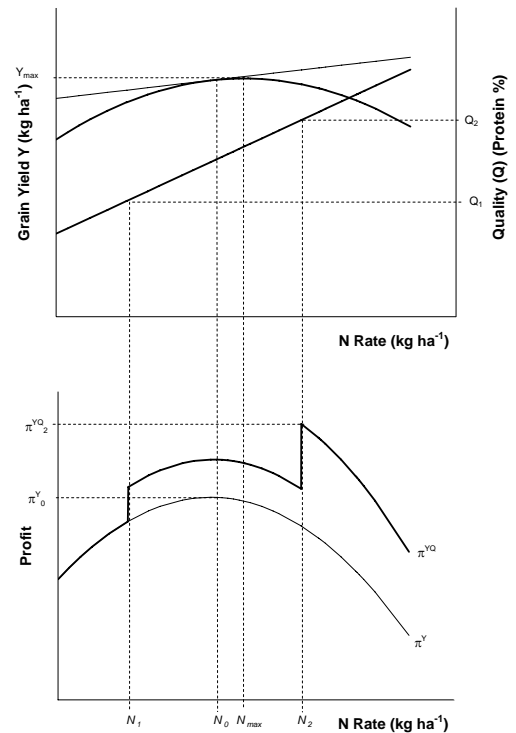


Fig 1. Grain yield, grain protein and profit as a function of N-fertilizer input with stepwise payments for different grain qualities

The bottom panel also illustrates the profit function (π^{YQ}) when quality as well as quantity is influenced by nitrogen. The discontinuity in the profit function results from having three prices based on the level of quality which is the pricing structure for German wheat. The price of wheat is assumed to be

$$P_Y = P_{Y,1} \text{ if } Q < Q_1 \text{ where } Q_1 = \alpha_0 + \alpha_1 N_1$$

$$P_{Y,2} \text{ if } Q_1 \leq Q < Q_2 \text{ where } Q_2 = \alpha_0 + \alpha_1 N_2$$

$$P_{Y,3} \text{ if } Q \geq Q_2. \quad (6)$$

The general shape of π^{YQ} is the same as π^Y but it jumps up with the output price increases at N_1 and N_2 . The optimal nitrogen rate considering yield and quality with the assumptions given in Figure 1 is at N_2 where the threshold for a higher wheat quality is just achieved. In the presented case, the threshold protein concentration for highest quality can only be achieved at the expense of yield penalties due to fertilization beyond the yield maximizing rate. Fertilizing for this quality is economically only justified if the price

difference for the qualities attained can compensate the grain yield loss and the additional fertilizer input. The extent of the yield penalty depends on the shape of the response functions for grain yield and grain protein.

On a field with heterogeneous growing conditions for the plants, it can be expected that yield and protein response of the crop varies in space. Fig 2 illustrates the implications of this variation for the economic response in two subfields. It is assumed that the field consists of two subfields with different yield and crop quality response to N fertilizer. Subfield "A" achieves baking crop qualities at lower fertilizer rates than subfield "B" (Note, that for subfield "A" the response with very low N-rates, which result in feed wheat, is not presented in the graph). The highest profit can be obtained with premium quality at a N-rate of N^{A*} . The other subfield (B) achieves only a lower crop quality, which requires much less N fertilizer N^{B*} in the economical optimum. With uniform management the economic response to N fertilizer will be as illustrated with the graph π^{AB} . Due to blending of the different qualities premium quality will only be achieved at higher N-rates as in subfield A. However, in this case the economically optimal fertilizer rate is with lower grain quality at N^{AB*} . Separate management of the subfields is economically superior if the area-weighted (ω_A, ω_B) maximum profits from the subfields are higher than the profit from the uniform managed field, which is subject to price differences for different qualities and the area weights (Eq.7).

$$\omega_A \pi^{A*} + \omega_B \pi^{B*} \geq \pi^{AB*} \quad (7)$$

In the case, when complete separation of subfields is not possible, site-specific fertilization or grain segregation or the combination of both could be an economically interesting option. In these cases comparative advantages of the subfields can best be exploited. However, the investment costs for the used technology have to be covered by the additional gross margins due to efficiency gains.

For a given field the following management options appear to be theoretically possible and this will be analyzed in more detail in this paper:

Option 1: Uniform management (UM) with uniform harvest (Reference)

With this management option the farmer has to make a decision about which product quality he wants to

produce together with the decision on the fertilizer input rate. The profit maximizing N rate is where the marginal economic returns equal the marginal costs of the fertilizer subject to the quality requirements of the wheat quality.

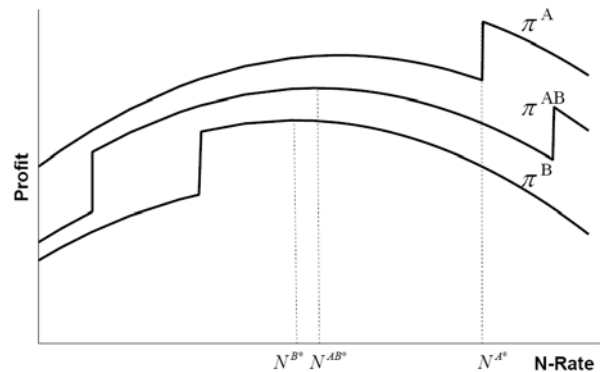


Fig 2. Economic response to fertilizer input on two modelled subfields (A, B) and on the whole field, when price is stepwise affected by quality

Option 2: Separate management (SM) of different zones, which have homogenous response characteristics

It may be possible to split the management of the subplots so that fertilization, harvest and marketing of the grains is separate. For each subplot decisions on fertilization, harvest and marketing have to be made independently in the same way as in option 1.

Option 3: Site-specific fertilization (SSF) and uniform harvest

Site-specific fertilization can capture comparative advantages of parts of the field and potentially can result in a more efficient use of fertilizer to achieve the required protein content for the whole field. The economically best fertilizer rates for i subplots can be found by solving the problem stated in Equation (8)

$$\text{Max} \left(\sum_{i=1}^n \omega_i Y_i(N_i) \cdot P_Y \left(\sum_{i=1}^n \omega_i Q_i(N_i) \right) - P_N \sum_{i=1}^n \omega_i N_i \right) \quad (8)$$

Option 4: Uniform fertilizer management with separation of different quality fractions (GS: grain segregation)

With this management option the farmer can separate

and blend the different qualities with the harvest or after harvest according to the different prices for the different quality grades. For this strategy maximal gross margins can be achieved by optimal blending of different qualities. The optimal blends can be calculated with a linear programming model.

III. MATERIAL AND METHODS

Data for this analysis were selected from a series of response trials, which were conducted from 1999 to 2001 with several wheat cultivars on different locations in Northern Germany [3]. Six cultivars were selected, which were planted on more than one location in a given year. The considered cultivars are suitable as baking wheat of two different qualities ("A" and "B"), if the grains meet the quality requirements. The quality requirements are, among others, protein content, which is a function of N fertilizer supply. While wheat with "A" quality needs at least 13.5 % protein content, wheat with "B" quality only needs 12 % protein content to meet the requirements. Wheat with protein quality lower than 12 % can only be sold as feed wheat.

Table 1 Data for Response analysis

Year	Cultivar	Number of subplots
1999	<i>Contur (B)</i>	2
	<i>Flair (B)</i>	2
	<i>Vivant (B)</i>	2
2000	<i>Contur (B)</i>	4
2001	<i>Batis (A)</i>	3
	<i>Drifter (B)</i>	2

On each location crop yield and grain quality response was analyzed over a range of 0 to 360 kg N ha⁻¹. For our analysis we assumed that the response of one cultivar on different sites within a given year reflects the potential range of response within a field. We estimated linear plateau and quadratic response functions for all yield response data; linear and quadratic response functions for protein response data.

To compare the different management options economically, highest returns above nitrogen fertilizer cost were calculated as a function of N fertilizer supply for the analyzed management options. We calculated the different economic potentials for six

different price structures for the different qualities according to Table 2.

Table 2 Wheat prices for different qualities from 2002 to 2007

Wheat quality	2002	2003	2004	2005	2006	2007
	€					
Feed	9.08	12.34	8.64	8.39	11.32	20.85
Baking (B)	9.85	12.66	9.02	9.19	12.42	22.05
Baking (A)	11.24	13.19	9.46	9.62	13.08	22.74

Source: [1]

The return above nitrogen fertilizer cost was calculated for the economic calculations without taking into account the costs for information gathering and site-specific fertilizer application or additional costs for grain separation. Fertilizer costs per kg Nitrogen were assumed 0.9 € kg⁻¹. Maximum return above fertilizer cost was determined analytically for the management options 1 and 2 according to equation 3. For management option 3 and 4 maximum return above fertilizer cost were determined with the excel solver maximizing net returns subject to fertilization on the different subfields and segregation of the grain into different qualities, respectively.

IV. RESULTS

A. Analysis of yield and protein response

The response analysis showed that for all modeled fields crop yield response showed comparable goodness of fit for quadratic and linear limitational functional forms. However, the AIC (Akaike information criterion) of the quadratic function was lower than that of the linear limitational function for all model fields. Therefore, we selected the quadratic function for modeling crop yield response. For protein response linear response functions were more appropriate according to the AIC criterion.

B. Economic Analysis of different management options

Table 3 shows the maximum gross margin from three different management options (uniform, separate management and site-specific fertilization) as average over the six different price structures given in Table 2. Separate management showed higher gross margins than uniform management for all cultivars. The

advantage of separate over uniform management ranged over all price structures from 2 to 21 € ha⁻¹. However, with specific price structures the range was wider from -17 to 32 € ha⁻¹. The negative value indicates an advantage of uniform management over separate management in the case when with uniform management it is economically justified to fertilize the whole field for baking quality, while with separate management this is only justified for specific subfields. This tendency was only evident when incentives for higher wheat qualities were high as with the price structures of the years 2006 and 2007.

Table 3 Net return above fertilizer cost from different management options (uniform management, separate management and site-specific fertilization)

Year	Cultivar	Net return above fertilizer cost		
		Management option		
		1 (UM)*	2 (SM)	3 (SSF)
		- €ha -		
1999	<i>Contur (B)</i>	969	973	973
	<i>Flair (B)</i>	1164	1165	1165
	<i>Vivant (B)</i>	634	642	642
2000	<i>Contur (B)</i>	1112	1132	1117
2001	<i>Batis (A)</i>	1008	1021	1027
	<i>Drifter (B)</i>	1114	1120	1120

*management option 4 (grain segregation) results in the same net returns

Source: Own Calculation

With site-specific fertilization maximum net return did not exceed the economic return with separate management, except in the case of *Batis* where baking quality was achieved more efficiently with site-specific fertilization than with separate management. However, site-specific fertilization requires investments in information gathering and application technologies, which have to be covered by increased returns from site-specific fertilizer management.

Table 4 shows N fertilizer supply, which is associated with the economic optimum of the different management options. Fertilizer rates with separate management were mostly below those of uniform management. The response analysis with the cultivar *Batis* showed higher application rates with separate management, which is due to the fact that one subfield showed positive yield response even with very high N fertilizer rates. With uniform management average response was supposed, which did not show this effect for the whole field.

Table 4 Nitrogen rates for different management options (uniform management, separate management, site-specific fertilization)

Year	Cultivar	Optimal level of fertilizer application		
		Management option		
		1 (UM)*	2 (SM)	3 (SSF)
		- Kg N ha ⁻¹ -		
1999	<i>Contur (B)</i>	309	281	308
	<i>Flair (B)</i>	262	262	262
	<i>Vivant (B)</i>	233	231	231
2000	<i>Contur (B)</i>	229	195	227
2001	<i>Batis (A)</i>	175	186	184
	<i>Drifter (B)</i>	228	228	226

*management option 4 (grain segregation) has the same nitrogen rates

Source: Own Calculation

The economic analysis of the separation of different qualities with uniform fertilization (management option 4) did not show higher net returns above fertilizer costs than uniform harvest in the economic optimum. Figures 3 and 4 show the typical response for uniform management with uniform harvest and grain segregation. It can be seen that with uniform harvest highest net returns can only be achieved within a small range of fertilizer rates. Hence, fertilization at these rates is associated with high risks. The separation of the different qualities can capture that risk by sorting out the grains with lower quality and ensuring the higher price at least for some part of the harvest. Over a range of fertilizer levels the separation can assure a profit level, which is more than 50 €ha⁻¹ above the level, which can be achieved with feed quality. It can be seen from the graphs in Fig 3 and 4 that the effect of grain separation was evident only within a specific range of fertilizer applied. This is because we considered only three and four different subfields with different responses for the respective model fields. For *Contur*2000, for example, at the rate of 230 kg N ha⁻¹, two of the subfields had baking quality. With fertilizer rates below that rate no subfield achieved baking quality. In reality, however, there are more than four response functions on a field, which result in a smoother trend for the economic returns.

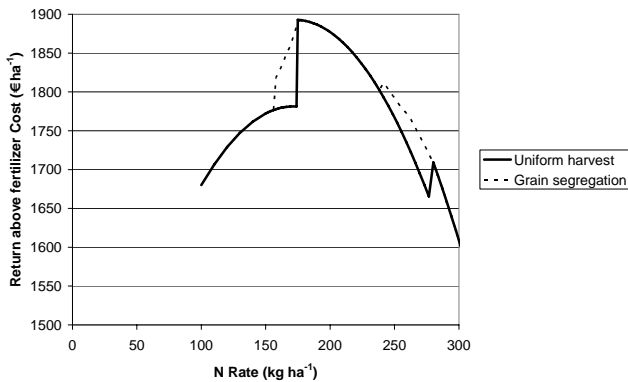


Fig 3. Returns above fertilizer costs with uniform and separate harvest (grain segregation) for the data set with *Batis* 2001 (Price structure 2007)

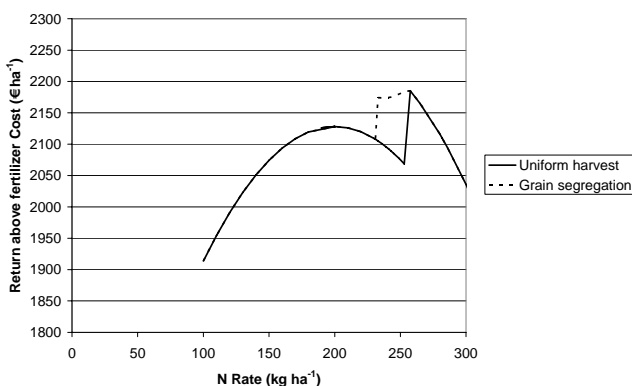


Fig 4. Returns above fertilizer costs with uniform and separate harvest (grain segregation) for the data set with *Contur* 2000 (Price structure 2007)

V. DISCUSSION AND CONCLUSION

The consideration of quality aspects with the choice of optimal input use makes the decision of optimal input use more complex and difficult than without quality considerations. Stepwise payments by quality let producers face great steps in the profit function of sometimes more than 50 €ha^{-1} . The extent of the steps depends on the yield and protein response and prices for the various qualities. At the time of fertilization, the farmer only has a vague idea of the prices and the exact response functions. Producers, therefore, would have to make their decision on input use under these uncertainties. The risk attitude will thus determine the input choice of the farmer to some extent. This is

especially true if higher qualities can only be obtained at the expense of yield penalties. In this case, fertilizer strategies for higher qualities are only justified if yield penalties can be compensated by higher prices for the wheat. In addition to the price risk, fertilizing for baking quality only provided higher returns within a small window of fertilizer application rates. An application rate below the necessary amount to achieve baking quality could result in a substantial reduction in the net returns of more than 50 €ha^{-1} . Usually it can be expected that farmers are aware of the risk and only fertilize for higher quality if the expected price for that quality is high enough and the potential loss of the net return in case of not achieving the necessary requirements is limited.

Site-specific management can help to capture possible gains for higher qualities. A separate management that included fertilization, harvesting and marketing resulted in an increase of up to 32 €ha^{-1} with high incentives for wheat quality. However, separate management can also lead to reduced returns, especially when high prices for quality grains justify fertilizing the whole field for baking quality. When fertilization for baking quality is economically not justified for the whole field, separate management of the different fields would provide high economic returns.

If separate management is not feasible, site-specific fertilization with uniform harvest may be an option to exploit the site-specific potentials. The economic potential is in the same range as separate management of the subplots. However, the response analysis from one cultivar indicates that site-specific fertilization may provide higher economic returns than complete separate management.

Instead of fertilizing for different qualities, another option is to fertilize uniformly and separate the harvested grains into different fractions of different quality grades (grain segregation). Although higher economic returns were not found with this strategy, compared to uniform management in the economic maximum, this technology could substantially reduce the risk of not meeting the higher quality threshold requirements by making the return above the fertilizer cost function more flat around its maximum. In this case, more than 50 €ha^{-1} can be saved, if the quality requirement for all grains from one field is just not

met. This option could be especially of interest, when grain qualities can only be achieved at the expense of yield losses or when fertilizer applications for high doses are restricted. However, the possibility to segregate different qualities creates incentives to apply higher doses of N fertilizer, which results in a less efficient use of the fertilizer. The resulting increased losses of nitrogen could therefore, burden the environment.

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- Corresponding Author: Andreas Meyer-Aurich
- Leibniz-Institute for Agricultural Engineering Potsdam-Bornim
- Max-Eyth-Allee 100
- 14469 Potsdam
- Germany
- Email: ameyer@atb-potsdam.de