
# Risk efficiency of site-specific nitrogen management with respect to grain quality

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***Abstract.*** *Profitability analyses of site-specific nitrogen management strategies have often failed to provide reasons for adoption of precision farming implements. However, often effects of precision farming on product quality and price premiums were not taken into account. This study aims to evaluate comparative advantages of site-specific nitrogen management over uniform nitrogen management with respect to aspects of risk, considering fertilizer effects on grain quality and price premiums. We developed a model field with two subfields representing different yield classes to investigate how consideration of grain quality affects the economic potential of site-specific nitrogen management and to what extent site-specific nitrogen management can have a risk-reducing effect compared to uniform nitrogen management. Results show that higher crop yields as well as higher protein contents of the grains can be achieved with site-specific nitrogen management compared to uniform nitrogen management. Higher grain quality and associated higher product prices result in higher economic benefit. Furthermore, a risk-reducing effect can be expected with site-specific nitrogen management by maintaining a certain grain quality with a higher probability.*

***Keywords.*** *Precision farming, variable rate application, Monte-Carlo simulation.*

## Introduction

Variable rate application of nitrogen (N) fertilizer to crops has been addressed since the early stages of precision farming (PF). The obvious reason for this is that N is the crop nutrient which is needed in the highest amount of all crop nutrients. While these reasons are intuitive, profitability of site-specific N application technologies have been under discussion. First of all, it is a challenge to assess profitability of PF technologies, since there is a lack of long-term data apart from a few sites (Yost et al., 2017). Furthermore, the economic advantage of PF technologies highly depends on the reference system compared and the associated costs considered (Gandorfer & Meyer-Aurich, 2017). Bullock et al. (2002) proposed using site-specific yield functions for the economic assessment of site-specific nutrient management. They found a net economic benefit around 7$ ha$^{-1}$ of using site-specific N application compared to uniform N management, while Lawes & Robertson (2011) calculated about 11€ ha$^{-1}$ net return after the additional costs were deducted. Schneider & Wagner (2008) reported 16€ ha$^{-1}$ of economic return with N sensor application where the costs for the sensor technology were not included. Various profitability analyses of site-specific N fertilization strategies have shown that there is no strong evidence whether investments in technologies of sensors and equipment to apply N site-specifically lead to high economic advantages as initially expected. Some argue that investments in variable rate application (VRA) technologies may not be paid off, when yield response to N does not vary strongly within a field (Anselin et al., 2004; Liu et al., 2006). Others argue that profit functions are generally flat, thus, limit the economic potential of site-specific input management (Pannell, 2006). However, the situation of low profitability of site-specific N fertilization may change, if such PF technologies do not only affect crop quantity but also crop quality (i.e. protein content). Site-specific N fertilization can help to reach a certain protein content (Morari et al., 2017; Bongiovanni et al., 2007) and, hence, the profitability of site-specific N fertilization can be improved, when its effect on grain quality is considered (Meyer-Aurich et al., 2010a; Meyer-Aurich et al., 2010b; Gandorfer & Rajsic, 2008). Meyer-Aurich et al. (2010b) and Gandorfer & Rajsic (2008) depicted this relationship indicating shifts in the profit function due to quality premiums for wheat. Nevertheless, this depiction is rather unrealistic to identify an economic optimum N rate based on the shifts, since the N mineralization from soil is different from year to year, thus, the total N input and average protein levels vary accordingly. Therefore, a recommendation for optimum N rate considering protein content cannot be made based on such profit functions.

Another concern regarding profitability of site-specific N application technologies is the uncertainty associated with it. Tozer (2009) made a risk assessment of precision farming and compared the standard net present value analysis with the real options approach with the focus whether an investment in precision agriculture can be more profitable if made now or in future. Whelan & McBratney (2000) reported that site-specific N management does not necessarily show advantages over uniform management accounting for farmers' risk aversion. However, most of the studies do not consider the impact of precision farming technologies in terms of utility with respect to risk attitudes of farmers. While the possibilities to consider site-specific variability in the field may be attractive for risk averse decision makers because sources of risk from heterogeneity of fields can be better addressed, investments in precision farming technologies imply specific risks, which need to be traded off.

We developed a conceptual framework modelling yield and protein response to N on a virtual field with two subfields representing high and low yield potentials. This study investigates, first, how the economic potential of site-specific N management changes, when a certain grain quality is thereby secured, and secondly if site-specific N management has a risk-reducing potential to meet a certain grain quality, thus, higher product prices. Our conceptual framework enables to assess the temporal effects of precision farming on crop yield and protein content, and to simulate a stepwise production function and calculate the expected value.

## Material and methods

### Research concept

Our study presents an approach based on transformation of yield and protein response data to N supply from a long-term field experiment. The response data were used to build yield response functions based on a normalization approach to simulate the implications of N fertilization on economic returns for a model field that consists of subfields with different yield classes (Karatay & Meyer-Aurich, 2018). We used normative data on input-output relations for N fertilizer supply and crop yields for different yield zones in Brandenburg, Germany, in order to generate yield response functions for respective yield zones. Our concept enables to identify the comparative cost structures between site-specific and uniform N management with the focus on risk analysis. We conducted partial budgeting regarding N fertilization for winter wheat considering three grain quality levels on a virtual field with two subfields representing high and low yield zones.

### Site-specific yield and protein response functions to nitrogen

*Data*

Crop yield response data for winter wheat (*Triticum aestivum* L.) were taken from a field experiment (1986-1999) in Dahlem/Berlin (Köhn et al., 2000). Protein response data were taken from the same experiment (1996-1998) in Dahlem (Ellmer et al., 2001).

**Table 1. Empirical data on yield response to nitrogen (Köhn et al., 2000) and protein response to nitrogen (Ellmer et al., 2001)**

| N fertilizer rate (kg/ha) | Yield (kg/ha) | Protein content (%) |
|---|---|---|
| 0 | 3250 | 9.8 |
| 60 | 5280 | 10 |
| 110 | 5680 | 12.2 |
| 160 | 5980 | 13.8 |

As normative data (Table 2), we used data on input-output dependencies reported in Hanff & Lau (2016). This is a data collection for economic assessment of agricultural production in the state of Brandenburg (Germany). The data provide input-output patterns including N fertilization rate for five differentiated yield zones in Brandenburg. In our analysis, yield-zone I and yield-zone III were used representing a high and a low yield zone for winter wheat production. We used the N fertilization rate and corresponding yield level for each yield zone with the assumption that they represent the respective optimum N fertilizer rate (Table 2).

**Table 2. N fertilizer rate and corresponding yield at five yield zones in Brandenburg (Hanff & Lau, 2016)**

| Yield zone | I | II | III | IV | V |
|---|---|---|---|---|---|
| Yield (kg/ha) | 7700 | 6500 | 5000 | 3800 | 2300 |
| N rate (kg/ha) | 170 | 144 | 111 | 84 | 51 |

*Estimation of site-specific yield and protein response functions*

We used the yield response data for winter wheat to estimate a quadratic yield response function to N by using ordinary least square method as follows:

$$f(N) = aN^2 + bN + c \tag{1}$$

where *f(N)* is yield (kg/ha), *N* is nitrogen fertilization rate (kg N/ha), *a* is the quadratic coefficient, *b* is the linear coefficient, and *c* is a constant.

We aimed to build yield response functions for each subfield derived from yield zones in

Brandenburg as:

$$f(N) = a_i N^2 + b_i N + c_i \quad (2)$$

where *i* denotes the subfield.

Protein response function *g(N)* was assumed to be the same at both subfields as a linear function of *N* empirically estimated from Dahlem experiment based on Ellmer et al. (2001):

$$g(N_i) = \alpha N_i + \beta \quad (3)$$

**Profitability calculation**

We performed a partial budgeting for net return over N fertilizer applied. Net return was found as revenue due to crop sales minus N fertilizer costs. The optimum N rates were calculated according to respective yield and protein response functions. We considered three product prices for winter wheat according to the protein content as a proxy for grain quality. In case above 13.5% of protein content was achieved, price for A-quality wheat was considered; between 13.5 and 12.5% protein content, price for B-quality wheat was considered; below 12.5%, price for feed quality was used.

**Table 3. Wheat prices of different quality (LfL, 2018)**

| Year | A-quality | B-quality | F-quality |
|---|---|---|---|
| | | (€/Mg) | |
| 2017 | 165 | 159 | 151 |
| 2016 | 162 | 156 | 145 |
| 2015 | 171 | 164 | 158 |
| 2014 | 180 | 170 | 158 |
| 2013 | 192 | 187 | 183 |
| 2012 | 259 | 252 | 246 |
| 2011 | 212 | 205 | 199 |
| 2010 | 232 | 218 | 186 |
| 2009 | 122 | 115 | 107 |
| 2008 | 151 | 142 | 132 |

Net return over nitrogen applied (€/ha) is calculated as:

$$NR = \sum_i^n \lambda_i \left[P_W(g(N_i)) \cdot f_i(N_i) - P_N N_i\right] \quad (3)$$

*NR*: Net return, $P_W$: Price of wheat (€/kg) depending on protein content *g(N)*, *f(N)*: Yield (kg/ha), $P_N$: Price of nitrogen fertilizer (€/kg N), *N*: Nitrogen fertilizer rate (kg N/ha), *i*: Subfield, and *λ*: Share of subfield in the total area.

In the case of site-specific nitrogen management, annual costs of a sensor system were deducted from net return. These were considered as 11 € $ha^{-1}$ $a^{-1}$ assuming a cropping area of 500 ha (OECD, 2016).

With uniform management, a single N fertilizer rate is applied across the field which consists of two subfields of equal size with different yield responses to N. The uniform N rate is the net return maximizing N rate of the average yield response function.

Site-specific N management (SSNM) applies N rate according to each subfield's yield response to N. In other words, this management system maximizes the net return of the whole field by applying individual optimum N rate in both subfields of equal size. Therefore, a higher net return can be achieved by site-specific N management than uniform N management.

For both uniform and site-specific nitrogen management, the default quality type was assumed to be B-quality. Therefore, initial optimum N fertilizer applications were adjusted to reach B-quality (minimum 12.50% of protein content).

### Uncertainty and risk analyses

In order to provide an array of possible net returns resulting of the considered management practices (uniform and SSNM), we ran Monte-Carlo simulations (5000 iterations) considering uncertainties regarding wheat prices depending on the grain quality, and N mineralization in the soil. All input parameters were modelled with a discrete uniform distribution *RiskDUniform* using @Risk (Palisade Corporation Software, Ithaca NY USA).

Based on the simulation results, we calculated expected value, conditional value at risk, and probability of a certain protein content.

## Results

Results indicate that site-specific N management increases crop yields and the expected value (mean) of net return by 21€ $ha^{-1}$ (Table 4). The economic benefit found in this study is higher than benefits calculated for wheat in other studies on SSNM, where no premiums for product quality were taken into account.

**Table 4. Results of Monte-Carlo simulations (n=5000) on net return for uniform nitrogen management and site-specific nitrogen management (SSNM)**

| | Uniform | SSNM |
|---|---|---|
| | (€/ha) | |
| Minimum | 364 | 358 |
| Maximum | 1545 | 1562 |
| Mean | 965 | 986 |
| Median | 901 | 934 |
| SD | 241 | 246 |
| CVaR(5%) | 557 | 566 |
| CVaR(10%) | 575 | 586 |

Compared to uniform management, the variance of net return of site-specific N management was higher. While the lowest observed value of net return was lower with site-specific N management than with the reference fertilizer strategy, the conditional value at risk was 9€ $ha^{-1}$ and 11€ $ha^{-1}$ higher at the lowest 5% and 10% respectively for site-specific N management. This indicates a small impact of site-specific management on risk efficiency. With site-specific management highest values for net return were achievable.

Cumulative probability of net returns illustrates that site-specific nitrogen management shows dominance over uniform management almost all around the simulation results (Figure 1). In the lowest bound, the net returns of the uniform nitrogen management show lower values because of the additional costs of site-specific nitrogen management for the sensor system.

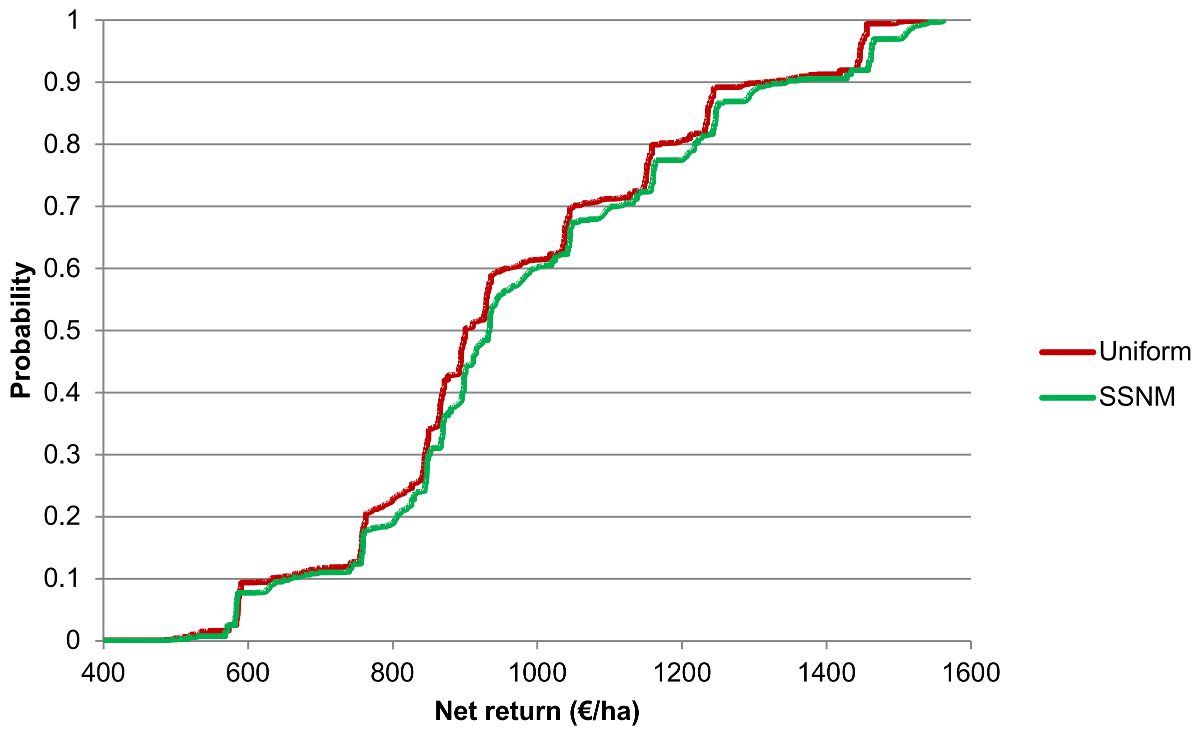


**Figure 1. Cumulative probability of net returns based on Monte-Carlo simulations (n=5000) for uniform nitrogen management and site-specific nitrogen management (SSNM)**

Site-specific N application resulted in higher protein content compared to uniform fertilization. SSNM shows advantages over uniform nitrogen management to maintain B-quality level (Table 5). For SSNM, 93% of the simulations, B-quality was achievable, thus, this reduced the probability of losing that critical quality level by 50% compared to uniform N management where 14% of the cases, the protein content was not high enough to achieve B-quality. Furthermore probability of reaching A-quality was considerably higher with SSNM.

**Table 5. Probability of upgrading to A-quality and losing B-quality for uniform and site-specific N management based on Monte-Carlo simulations (n=5000)**

| Probability | Uniform | SSNM |
|---|---|---|
| Achieving A-quality | 7% | 29% |
| Losing B-quality | 14% | 7% |

Cumulative probability of protein contents indicates that SSNM yielded higher protein contents in all the simulation iterations and thus shows dominance over uniform management at every level. In the lowest 10% bound, B-quality could not be reached by uniform N management, while within the same bound, SSNM assured B-quality with a considerable difference. In the upper bounds, the advantage of SSNM maintained (Fig. 2).

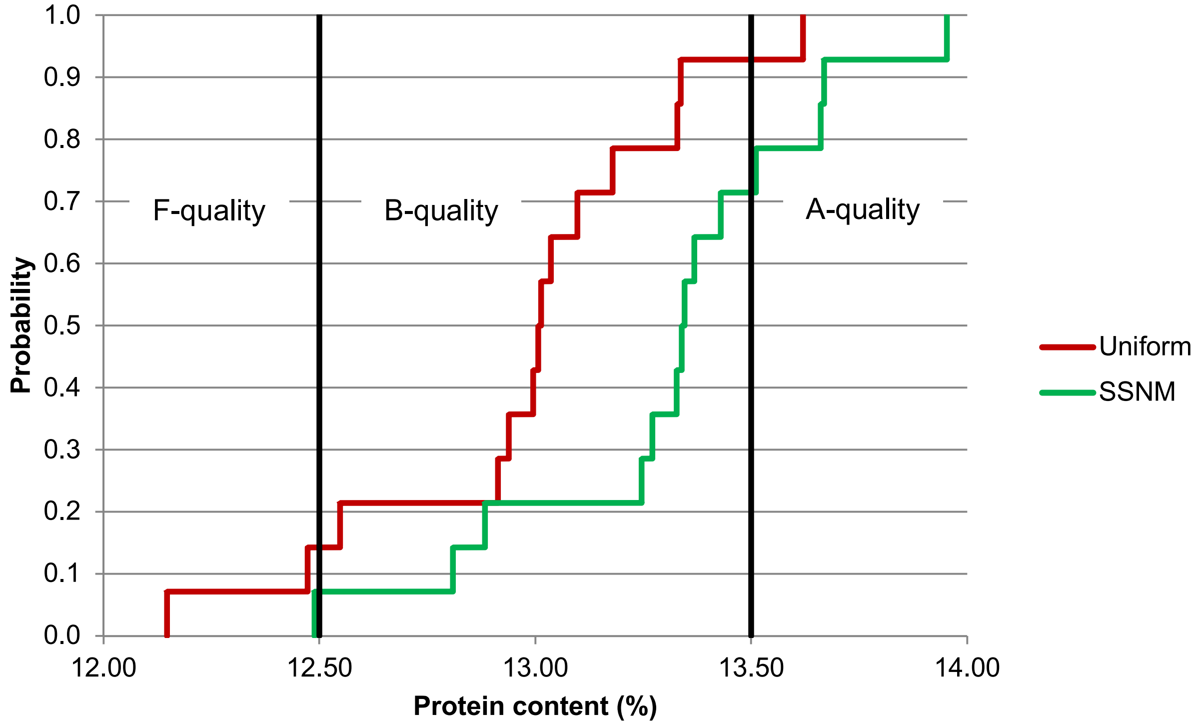


**Figure 2. Cumulative probability of protein contents based on Monte-Carlo simulations (n=5000) for uniform nitrogen management and site-specific nitrogen management (SSNM)**

## Conclusions and outlook

In conclusion, it can be stated that site-specific N management of wheat can contribute to higher net returns than uniform management. For a risk averse decision maker, the additional benefit of SSNM has to be traded off against the higher variance of net returns and the lower minimum value for net returns. However, a higher conditional values at risk indicates a risk-reducing effect of SSNM.

Variable rate technologies for site-specific N application may offer further advantages by increasing the probability of achieving a certain grain quality, for instance, in case of an N supply restriction. Moreover, the importance of site-specific N management may be higher, if positive external effects (e.g. lower N leaching and greenhouse gas emission) can be internalized.

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