Evaluation of mapping and on-line nitrogen fertilizer application strategies in multi-year and multi-location static field trials for increasing nitrogen use efficiency of cereals

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Abstract

Mapping and on-line (sensor) variable rate nitrogen fertiliser application strategies were tested in static field trials for three years and in several locations. We determined whether they can enhance nitrogen use efficiency of cereals as compared to optimal uniform nitrogen application while still maintaining yields. In general, high yields were found on field sites representing moderate infield variability. Despite highly contrasting weather conditions between years, similar responses were observed between lower and higher yield zones and the effects of the different strategies were found to be relatively consistent. The results indicate considerable potential to increase nitrogen use efficiency while simultaneously maintaining yields. The mapping approach, which considers the long-term yield potential, indicated substantial gains for the environment in areas of lower yield productivity and fertile colluvial deposit zones with average savings of 34 and 17 kg N ha^{-1}, whereas the sensor approach led to a reduction in nitrogen application on sites with high yield productivity of about 8 kg N ha^{-1}. A combination of the approaches could further increase the benefit for the environment and represent a new standard for the good code of agricultural practice in heterogeneous fields.

Keywords: environment, nitrogen, sensor, site-specific, variable rate, yield productivity

Introduction

Strategies for site-specific nitrogen fertilizer application may focus on optimising yield and on reducing the spatial infield variability of crops (Wollring *et al*., 1998). As such, environmental concerns may not be prioritised. Environmentally sound fertilizing systems should both maintain high yields and improve nitrogen efficiency. Strategies that are well adapted to site-specific yield productivity areas should fulfil both goals. Khosla and Alley (1999) found that using VRA on a 14.4-ha field in Virginia reduced total N applied by 22 kg N ha^{-1} without a reduction in grain yield when comparing with a uniform N treatment.

Site-specific farming can contribute in many ways to long-term sustainability of production agriculture, confirming the intuitive idea that precision agriculture should reduce environmental loading by applying fertilizers only where they are needed, and when they are needed (Bongiovanni and Lowenberg-Deboer, 2004). However, nutrient recommendations corresponding to within field site-specific characteristics are rarely available (Robert, 2001). In contrast there is a substantial body of information available describing the infield variability itself. Implementing the knowledge gained in sound management practices is clearly lagging. This is true not only for very recently developed sensor-based approaches that allow the detection of biomass and nitrogen status on the go, but also for mapping approaches that mostly report results from short-term studies. The goal of this study was to test whether targeted, site-specific nitrogen fertilizer application allows for increasing nitrogen efficiency while also maintaining yields. This was done by means of static, multiple-year field trials. As such, our work directly addresses the lack of well-documented comprehensive studies in this area.

Universal nitrogen fertilizer application strategies for heterogeneous fields do not exist. This is already evident by the fact that only mapping approaches, on-line approaches or their combination (i.e., on-line approaches with map overlay) are currently tested. Additionally, there is no consensus as to how lower or higher yield productivity zones should be treated. Increasing nitrogen input to weaker crop stands may enhance yields, but might not be particularly environmentally friendly. Alternatively, it has been variously argued that higher yield productivity areas should or should not receive higher nitrogen inputs. Khosla *et al*. (2002) and Hornung *et al*. (2003) demonstrated N input optimisation via high N application rates in more productive areas and low N rates in less productive area has potential to increase NUE. In contrast, Griepentrog and Khyn (2000) demonstrated N input optimisation via reduced N application in highly productive areas. The situation becomes even more complicated in trying to generalize the strategies for regions that differ in climate and, even more so, in trying to account for the annual variation in climate, which may interact differently at different locations.

To gain such information and to improve our knowledge in this area, different nitrogen fertilizer application strategies (including mapping and sensor approaches) were tested and compared to uniform nitrogen fertilizer application. Static field trials lasting several years were conducted on six fields in three different regions of Bavaria, Germany, receiving different amounts of annual rainfall. The trial years encompassed a large range in climatic conditions from temperate and humid to hot and dry conditions. The sites investigated also do not represent extremes, but rather include fields that differ only moderately in their infield variability. Crop rotations included cereals, sugar beet and maize. The results from ten field trials obtained with cereals are reported in this study. It is expected that the results will facilitate the establishment of appropriate strategies for site-specific nitrogen fertilizer application with a particular emphasis on environmental gains.

Materials and methods

Various site-specific nitrogen fertilizer application strategies were tested in three regions in Southern Germany with different climatic conditions and different soil properties. For the sites Gieshügel (latitude 49°46`27.63”; longitude 10°1`16.25”), Adelschlag (48°56`21.95”;11°9`16.20”) and Scheyern (48°29`45.97”;11°26`23.78”), respectively, long-term averages for temperature were 8.9, 8.0, 7.6°C, whereas those for annual rainfall were 550, 670, 805 mm. Field sizes varied between 6 to 30 ha. Soil types were silty loam to loamy clay, sandy loam and moderately stony loam, and sandy to clayey loam. The major sources of infield variability were soil depth and clay content, soil texture and shallowness, and soil texture and topography. Soil fertility levels except for nitrogen were adequate such that they were not yield limiting. Potassium and phosphorus removal by crops was regularly replaced. Soil physical and chemical properties of all sites were previously intensively characterised. This together with concomitant measurements of soil matric potentials (data not shown) and previous more mechanistic investigations of the relationship between yield and varied water supply allow identifying water and nitrogen supplies as yield limiting factors (Geesing *et al*., 2001). Experiments were started in 2000 in Scheyern and in 2002 for the other two locations.

Crop rotations on the respective sites included winter wheat and maize for Scheyern; winter wheat, winter rye, sugar beet in Adelschlag; and winter wheat, triticale, sugar beet, spring wheat in Gieshügel. This report focuses on cereals.

Cultivation was performed according to the code of good agricultural practice. Three nitrogen fertilizer application strategies were included.

Strategy I represented uniform nitrogen fertilizer application corresponding to the farmers' optimised practice and was performed according to official recommendations, including analysis for residual soil nitrogen early in the season (Hege *et al*., 2001).

Strategy II represented differential nitrogen application based on a mapping approach. Previously obtained information from long-term yield maps, aerial spectral remote sensing (Selige and Schmidhalter, 2001) and proximal reflectance based sensing (Schmidhalter *et al*., 2001a) as well as soil maps based on electromagnetic mapping by EM38 (Schmidhalter *et al*., 2001b) were used to delineate areas of lower or higher yield productivity. A tractor-based radiometer, similar to the Yara sensor, was used to measure reflectance with a spectral detection range from 400 to 1000 nm and a pixel distance of 3.3 nm. Details of spectral indices used have been described elsewhere (Schmidhalter *et al*., 2003). Nitrogen was applied based on the expected yield productivity and the soil properties that were investigated (primarily soil water availability and nitrogen mineralisation potential). In general, this means low N input on zones with reduced soil water availability and lower yield expectation and vice versa. Nitrogen input was also reduced to colluvial deposit zones with increased water availability and enhanced soil nitrogen supply. For this approach, fertiliser application was purposely not optimised a priori to learn more about the response of the investigated zones.

Strategy III represented an on-line strategy consisting of a sensor controlled fertilizer application using the Yara N-sensor (Lammel *et al*., 2001). At high sensor values the N demand is low because of the good plant N and biomass status of the crop and vice versa. To avoid an inappropriately high N application rate to thin or badly developed crops with low biomass and chlorophyll contents a biomass cut-off value has been used (Lammel *et al*., 2001).

For all three areas, the mapping approach was compared to uniform nitrogen fertilizer application; a comparison involving an on-line sensor approach was also performed exclusively in Gieshügel. The trials were performed as static strip plots (non-randomised, 12 or 15 m broad with 6 to 11 replications per nitrogen fertilising strategy depending on the field). N application rates with the 3 strategies can be derived from the information given in Tables 1 and 2 and is explained below.

The relative nitrogen and biomass status of the cereal crops were mapped several times throughout the growing season by reflectance sensor. On all fields intensive plot harvesting was performed on more than 100 plots, each 10-15 m^2 in area. Additionally, straw and grain yield was determined on each field by representative hand cuts from six to seven representative sites within the field with 6-to-8 replications, each 0.4 m^2 in area, and yield monitor data from a combine harvester were obtained. Subsequently, nitrogen content in the grain and straw was determined in the laboratory and nitrogen uptake was calculated.

Apparent nitrogen use efficiency was calculated as the nitrogen uptake by the grain divided by the amount of nitrogen fertilizer applied. A more commonly used definition for nitrogen use efficiency is grain production per unit of N available in the soil. However, this requires direct measurements of available N that is not feasible in large field studies and is difficult to measure accurately. In lieu of such measurements one can substitute available N for fertilizer rate in a simplified definition of nitrogen use efficiency (Moll *et al*., 1982).

Mean separation of treatment effects in this study was accomplished using Tukey´s least significant difference (LSD) test. Probability levels lower than 0.05 were categorised as significant. All data analyses in this study were accomplished using the SPSS System for Windows, version 12.0.1 (SPSS Inc., 2003).

Results and discussion

Yields for winter wheat, winter rye and triticale generally exceeded 8.8, 9.9, and 7.9 t ha^{-1}, ranging up to 12 t ha^{-1} (Table 1). The only exception was a single rather low yielding winter wheat cultivar in 2003 with 5.2 t ha^{-1}.

Despite the largely differing weather conditions between years, similar responses were observed for areas with either lower or higher yield productivity and consistent effects of the different strategies were found.

Yield differences between areas of lower and higher yield productivity differed among years and were in general more accentuated by annual weather conditions than by fertilizer treatments (Table 1). On the uniformly fertilized areas, yields in 2002 in areas with lower yield productivity were 13% lower than those of the higher yield productivity areas. Differences between these zones within this treatment were more marked in 2003 (32%) and least in 2004 (5%), where yield differences were smoothed by the ample, evenly distributed rainfall and warm weather conditions in this year, and enhanced by the hot and dry weather conditions. Although differences between areas of lower and higher yield productivity differed between years, the consistent pattern obtained in this study indicates a fairly static character to lower or higher yield productivity zones. This contrasts with observations from other studies (Blackmore *et al*., 2003). Results from this study indicate that relative yield productivity areas can be precisely delineated using remote or proximal sensing information (Selige and Schmidhalter, 2001; Schmidhalter *et al*., 2001a). The information obtained from yield monitor, being subject to error and relying on careful calibration, could reflect the yield more absolutely. However, the possibility for developing maps of classified management based on similar quality yield maps as obtained from farmers appears limited because of the high frequency of erroneous data sets, systematic errors in the recorded data and their restricted yield predictive ability (Joernsgaard and Halmoe, 2003). Practical application of yield mapping to identify zones has been plagued by spatial and temporal variation in measured yield (Sadler *et al*., 1995). More consistent information reflecting relative yield zones was obtained in this study and a previous one (Schmidhalter *et al*., 2001b) gained from spectral information. Therefore the latter is considered to represent a powerful approach for the future for the delimitation of relative yield productivity areas. This supports a previous notion by Mulla and Schepers (1997) that remote sensing is especially appealing to identify management zones because it is non-invasive and low in cost.

Areas with high yield productivity (including colluvial deposit areas) did not display any significant yield differences between site-specific and uniform nitrogen application strategies (Table 1). This is in line with observations by Griepentrog and Kyhn (2000) for a highly productive agricultural area in the county of Schleswig-Holstein. A slight tendency for increased yields was observed in areas with lower yield productivity for the sensor approach as compared to the other strategies. More clearly, yields in the lower yield productivity areas were reduced by an average of about 4% by the mapping approach (8.2 vs. 8.5 t ha^{-1}), with maximum decreases of up to 9% being observed. Average nitrogen application under the uniform strategy was 183 kg N ha^{-1}. By contrast, average nitrogen application as guided by the mapping approach was reduced by 34 kg ha^{-1} and increased by about 11 kg ha^{-1} in the lower and higher yield productivity zones, respectively, as compared to uniform nitrogen application. The nitrogen input was consistently reduced by about 17 kg N ha^{-1} on the colluvial zones by the mapping strategy. When considering lower, medium and higher yield productivity areas in equal shares, the mapping approach resulted in an overall reduced nitrogen input of 26 kg N ha^{-1} as compared to uniform nitrogen fertilizer application.

As compared to uniform nitrogen application, the apparent nitrogen use efficiency under the mapping strategy was increased over the whole field by 3% (Table 2). This average includes significant increases of 12% (with maximum values reaching 28%) and 7% on the lower yield productivity and colluvial zones, respectively, and a decrease of 5% on the higher yield productivity areas. The sensor approach significantly decreased nitrogen use efficiency by 10% on the lower yield productivity areas and increased it slightly, but not significantly, on medium and higher yield productivity areas.

All experiments were conducted at nearly optimal supplies of nitrogen as indicated by high apparent nitrogen fertilizer use efficiencies of 98% and 101% (averaged over the whole field) for the uniform and mapping strategy, respectively. The results show that under otherwise already optimised cultivation conditions, further improvements in nitrogen use efficiency can be obtained by variable rate nitrogen fertilizer application.

The mapping strategy dramatically improved the apparent efficiency of nitrogen use on the lower yield productivity and colluvial zones while still largely maintaining yields (9 t vs. 9.2 t ha^{-1}) as compared to uniform management. The end average savings of 26 kg N ha^{-1} clearly benefits the environment. This result is very promising because improvements were obtained at yield levels that were already fairly high and with only relatively moderate differences in infield variability.

The sensor approach produced mixed results. On sites with lower yield productivity and weak crop stands, higher N rates were applied by the sensor approach as compared to uniform application. However, this did not significantly increase the yield and the N uptake by the plants because of limited water availability evident from previous soil investigations and concomitant measurements of the soil water status (data not shown) and because the algorithm used for nitrogen fertilisation by this approach is not yet optimised with regard to nitrogen use efficiency on lower yield productivity areas. That being said, the sensor approach showed other advantages in these areas, including slightly increasing the yield in general and, more importantly, homogenising crop stands (Ebertseder *et al*., 2003). By contrast, the online N-sensor (strategy III) could readily detect increased nitrogen supplies in soils with sufficient water availability. As such, the sensor approach obtained comparable yields with slightly decreased protein contents as for the other strategies while greatly reducing nitrogen application on sites with high yield productivity.

These experiments were conducted to test the sensitivity of the mapping approach for reducing nitrogen input on lower yield productivity areas and to test whether increased nitrogen input to the higher yield productivity areas are advantageous. The results show that further optimisation can still be achieved. In higher yield productivity areas that are already under optimum fertilizer application, there is no need to increase the fertilizer dose as compared to the levels from uniform application. This will result in further savings of nitrogen. From an environmental point of view, the current mapping approach seems to be optimal for the lower yield productivity areas. It is expected that a slightly less-reduced fertilizer input in such areas might equalize yields by producing significant gains in fertilizer use efficiency. This is supported by the results obtained with the sensor approach. The strategy adapted for the colluvial deposit zones was optimal with regard to yield and nitrogen use efficiency.

It is already evident from the results of this study that further improvements are highly likely with more marked differences in infield yield productivity. The results also clearly show that nitrogen use efficiency could particularly be improved under less optimal conditions (e.g., as in 2003). Yields in lower yield productivity areas, which are limited by the available water in the soil, can be increased markedly in years with ample and even rainfall (Geesing *et al*., 2001). In fact, high yields and minimized yield differences between lower and higher yield productivity areas were achieved in two out of the three years under investigation in this study. It also seems likely that further improvements can be obtained by combining mapping and sensor approaches. Combining the use of management zones with crop-based in-season remote sensing has been suggested by others as well (Schepers *et al*., 2004).

Conclusions

Our results, derived from a multi-year and multi-location field study, recommend the adoption of variable rate nitrogen fertilizer application. The consistency of the results, even in the light of the highly variable annual weather conditions, allows further generalization of the information obtained and gains from site-specific nitrogen fertilization to be estimated. A sensible increase in

Table 1. Effects of three different nitrogen fertilising strategies (uniform application, mapping and sensor approach) on the yield of cereals in different yield productivity areas in different fields and regions for 2002, 2003 and 2004.

Location	Year	Field	Crop	Yield productivity Area	Nitrogen fertilising strategy uniform Crop yield (t ha^{-1})	mapping	sensor
Scheyern	2002	A17	winter wheat	Lower	8.84Aa[1]	8.41Aa	
				high	9.47Ba	9.52Ba	
				colluvium	9.97Ca	10.02Ca	
	2003	A16	winter wheat	Lower	5.38Aa	5.55Aa	
				high	5.23Aa	5.20Aa	
				colluvium	6.26Ba	6.30Ba	
	2004	A17	winter wheat	Medium	10.87ABa	10.10Ab	
				high	10.64Aa	10.71Ba	
				colluvium	11.17Ba	11.05Ba	
Gieshügel	2002	Wald	triticale	Lower	7.88Aab	7.19Aa	8.16Ba
				Medium	9.21Ba	9.34Ba	9.47Ba
				High	10.03Ca	10.13Ba	10.04Ba
	2004	Wald	winter wheat	Lower	8.46Aa	9.34Aa	8.66Aa
				Medium	9.45Ba	9.34Aa	9.76Ba
				High	9.71Ca	9.47Ba	9.45Ba
	2003	Pfad	spring wheat	Lower	4.32Aa	4.23Aa	3.97Aa
				Medium	5.69Ba	5.65Ba	5.55Ba
				High	6.64Ba	6.47Ba	6.73Ca
	2004	Pfad	winter wheat	Lower	10.92Aa	10.30Aa	11.15Aa
				Medium	11.96Ba	11.76Ba	12.02Aa
				High	11.88ABa	12.04Ba	11.74Aa
Adelschlag	2002	Schlag 4	winter rye	Lower	9.88Aa	8.95Ab	
				High	10.26Aa	10.71Bb	
	2004	Schlag 4	winter wheat	Lower	9.34Aa	9.23Aa	
				High	10.11Ba	9.68Ab	
				colluvium	9.48ABa	9.54Aa	
	2004	Seuvers	winter wheat	Lower	9.22Aa	8.38Ab	
				high	11.67Ba	10.86Bb	
				colluvium	11.61Ba	11.59Ba	

[1]Means in column within yield productivity areas in each year and site followed by the same uppercase letter are not significantly different at $P = 0.05$ according to Tukey´s LSD test. Means in row within nitrogen fertilising strategy in each year followed by the same lowercase letter are not significantly different at $P = 0.05$ according to Tukey´s LSD test.

Table 2. Effects of three different nitrogen fertilization strategies (uniform application, mapping and sensor approach) on the apparent nitrogen use efficiency of cereals in different yield productivity areas in different fields and regions for 2002, 2003 and 2004.

Location	Year	Field	Crop	Yield productivity Area	Nitrogen fertilizing approach uniform	Mapping	sensor
					Nitrogen use efficiency (%)		
Scheyern	2002	A17	winter wheat	Lower	83Aa[1]	93Ab	
				high	90Ba	91Aa	
				colluvium	96Ca	106Bb	
	2003	A16	winter wheat	Lower	71Aa	91Ab	
				high	69Aa	66Ca	
				colluvium	82Ba	79Ba	
	2004	A17	winter wheat	Lower	95Aa	98Aa	
				high	95Aa	96Aa	
				colluvium	104Ba	107Bb	
Gieshügel	2002	Wald	triticale	Lower	97Aa	102Aa	86Ab
				Medium	110Ba	112Ba	106Ba
				High	124Ca	100Ab	125Ca
	2004	Wald	winter wheat	Lower	95Ab	139Aa	88Ab
				Medium	105Aa	113Ba	117Ba
				High	107Aa	96Cb	108Aba
	2003	Pfad	spring wheat	Lower	67Aa	76Aa	58Aa
				Medium	84Ba	84Aa	86Ba
				High	92Bb	83Aa	103Ba
	2004	Pfad	winter wheat	Lower	123Aa	123Aa	112Aa
				Medium	136Aa	134Aa	131Ba
				High	137Ab	122Aa	132Bb
Adelschlag	2002	Schlag 4	winter rye	Lower	88Aa	86Aa	
				High	90Aa	93Ba	
	2004	Schlag 4	winter wheat	Lower	88Aa	97Ab	
				High	100Ba	89Ab	
				colluvium	100Ba	128Bb	
	2004	Seuvers	winter wheat	Lower	91Aa	100Ab	
				high	114Ba	121Bb	
				colluvium	117Ba	112Ba	

[1]Means in column within yield productivity areas in each year and site followed by the same uppercase letter are not significantly different at *P* = 0.05 according to Tukey´s LSD test. Means in row within nitrogen fertilising strategy in each year followed by the same lowercase letter are not significantly different at *P* = 0.05 according to Tukey´s LSD test.

the already high yields by using site-specific farming is not possible. Site-specific farming can increase efficiency and reduce environmental impacts. In general, it appears that potential benefits to the environment of site-specific nitrogen fertilizer application increase the higher the yield differences on a field are and the less favourable the weather conditions are. However, the proportion of the lower yield productivity zones or highly fertile colluvial deposit areas on the whole-field level will also affect these benefits.

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