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Comparison of uniform control and site-specific model-based nitrogen prescription in terms of grain yield, nitrogen use efficiency and economic aspects in a heterogeneous corn field

Vergleich einer einheitlichen (Kontrolle) und einer teilflächenspezifischen Modell-basierten Stickstoff-Düngeempfehlung hinsichtlich Ertrag, Stickstoffnutzungseffizienz und Nettoertrag in einem heterogenen Maisschlag

Abstract

In Europe, and especially in Germany, the land area cultivated with corn over the last decade has continuously been increasing. Several studies indicated that corn production has a high risk of nitrogen leaching, thus the current nitrogen management strategy needs to be verified and compared with new management strategies. The objective of this study was to investigate and to evaluate uniform (control) and model-based (site-specific) nitrogen management strategies in terms of corn grain yield, nitrogen use efficiency and economic aspects. Field trials were conducted at an experimental station as part of Hohenheim University over a three-year period (2006–2008). Nitrogen application rate was varied to meet the given heterogeneity on the field. The crop growth model APOLLO was employed with using (site-specific) input data, including soil texture, weather, cultivar, management and historical yield data, in order to model corn yield depending on nitrogen fertilization rate variations.

In the experimental design, the field was separated in 48 management units. Within each management unit, a uniform control treatment and a site-specific model-based treatment were applied.

For the nitrogen application, a map was created and the fertilizer was broadcast accordingly at 130 kg N ha^{-1} for uniform control treatment and 100–210 kg N ha^{-1} for the site-specific treatment in line with the model results. Corn grain yield was acquired with a yield-mapping device on a combine harvester.

The two different nitrogen management strategies resulted in yield advantages for the model-based treatment compared to the uniform control treatment. Concerning corn grain yield and marginal net return, significant differences were determined between both nitrogen treatments. However, no significant differences were found for nitrogen use efficiency between the uniform control and the site-specific model-based nitrogen treatments. Further investigations of yield driving factors need to be performed in order to optimize corn grain yield according to a given within field heterogeneity.

Key words: Corn, nitrogen rate, yield, variability, model

Zusammenfassung

Im letzten Jahrzehnt ist die Anbaufläche zur Maisproduktion in Europa und insbesondere in Deutschland, kontinuierlich angestiegen. Zahlreiche Studien zeigen, dass die Maisproduktion mit einem hohen Risiko der Stickstoffauswaschung verbunden ist, weshalb die gegenwärtige Strategie des Stickstoffmanagements überprüft und mit neuen Managementstrategien verglichen werden muss.

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Ziel dieser Studie war, eine einheitliche (Kontrolle) und eine teilflächenspezifische (Modell-basierte) Strategie des Stickstoffmanagements hinsichtlich Kornertrag, Stickstoffnutzungseffizienz und ökonomischen Aspekten der Maisproduktion zu untersuchen und zu bewerten. Auf der Versuchsstation der Universität Hohenheim wurde über einen Zeitraum von drei Jahren (2006–2008) ein entsprechender Feldversuch durchgeführt. Die Aufwandmenge für Stickstoff wurde innerhalb des Schlages variiert, um die vorhandene Heterogenität des Schlages zu berücksichtigen. Das Pflanzenwachstumsmodell APOLLO wurde eingesetzt, um mit Hilfe (teilflächenspezifischer) Eingangsdaten, wie Bodentextur, Wetter, Sorte, Management und historischen Ertragsdaten den Kornertrag des Mais in Abhängigkeit unterschiedlicher Stickstoffdüngermengen zu ermitteln.

Für das Versuchsdesign wurde der Schlag in 48 Managementeinheiten unterteilt. In jeder dieser Managementeinheiten wurden die einheitliche Kontrolldüngung und die teilflächenspezifische (Modell-basierte) Düngung ausgebracht.

Für die Ausbringung des Stickstoffdüngers wurde eine Applikationskarte erstellt, anhand derer in der Kontrollvariante 130 kg N ha^{-1} und in der Modell-basierten Variante 100–210 kg N ha^{-1} (entsprechend der Simulationsergebnisse des Pflanzenwachstumsmodells) ausgebracht wurden. Der Kornertrag des Mais wurde mit Hilfe der Ertragskartierung des Mähdreschers erfasst.

Die unterschiedlichen Strategien des Stickstoffmanagements resultierten in geringen Ertragsvorteilen der Modell-basierten Variante, verglichen mit der Kontrollvariante. Hinsichtlich des Kornertrags und des Nettoertrags lagen signifikante Unterschiede zwischen den beiden Stickstoffmanagement-Strategien vor. Hinsichtlich der Stickstoffnutzungseffizienz konnten allerdings keine signifikanten Unterschiede zwischen der Kontrolle und der Modell-basierten Variante ermittelt werden.

Um den Kornertrag in Mais unter Berücksichtigung der vorherrschenden Heterogenität des Schlages zu optimieren, müssen weitere ertragslimitierende Faktoren untersucht werden.

Stichwörter: Mais, Stickstoffdüngung, Ertrag, Variabilität, Modell

Introduction

The area utilised for corn production has continuously been increasing over the last years (FAO, 2012). Across Europe the harvested area of corn increased from 13,707,207 ha in 2000 to 14,208,690 ha in 2010 (+3.7%), whilst in Germany there was an increase of 28.5% (360841 ha in 2000, 463600 ha in 2010). The expansion of corn production area in Germany is mainly driven by the given law to increase the share of renewable energy at the total energy production (EEG, 2012). A similar situation also applies to other EU-countries, e.g. Czech Republic (Losak et al., 2010). Consequently, to aid in achieving high biomass for corn and silage production, an increased input of nitrogen fertilizer into farming systems is therefore also expected. Especially in developed countries up to 400 kg N ha^{-1} is used for silage production (Hatch et al., 2002) but often only a share of the applied nitrogen is taken up by the crops (IFA and FAO, 2001), and the remaining nitrogen in the soil is a potential source of nitrogen pollution (Lægreid et al., 1999; Haag and Kaupenjohann, 2001; Hatch et al., 2002). In several studies continuous corn production has been identified as providing the greatest amount of nitrate into the groundwater through surface drainage (Kanwar et al., 1993; Weed and Kanwar, 1996; Randall et al., 1997) and consequently led to an increased nitrate concentration in the groundwater (Schröder et al., 1996; Van Dijk et al., 2004). Studies of Maidl (1990) and Aufhammer et al. (1996) showed that the utilization of nitrogen could be increased when nitrogen applications were split into two applications. However, due to technical limitations, nitrogen mineral fertilizer application in corn production is normally scheduled before or during the seeding process or within the first weeks after seeding. Low nitrogen uptake in the beginning and at the end of the growing season leads to high amounts of nitrogen in the soil after corn production (Lambert et al., 2002). Thus, in order to avoid environmental pollution, the nitrogen application rates need to be adapted to the current demand of the plants. Precision farming technologies offer great potential to match crop nitrogen demand with nitrogen application rates and thus taking the existing in-field variability in nitrogen utilization into account. Many studies in this area deal with effects of site-specific nitrogen application on corn yield and quality (Oberle and Keeney, 1990; Schmidt et al., 2002; Ferguson et al., 2002; Katsvairo et al., 2003; Roggenbuck et al., 2004; Miao et al., 2006). Some studies present the investigation of different management zones (Koch et al., 2004; Chang et al., 2004; Casey et al., 2006) and other studies focus on the economics of variable nitrogen prescription (Thrikawala et al., 1999; Mamo et al., 2003; Anselin et al., 2004; Koch et al., 2004). However, only a few studies compare uniform and site-specific nitrogen application rates within the same site (Babcock and Pautsch, 1998) or investigate the implementation of crop growth models to optimize nitrogen application rate for corn under aspects of precision farming (Paz et al., 1999; Thorp et al., 2004). However, the incorporation of spatial and temporal variability in nitrogen recommendations has the potential to increase fertilizer use efficiency and enable producers to stay within the limits imposed by current and future policies (Link et al., 2006a).

In our study the main focus was drawn on the comparison of uniform nitrogen application rates (as control) with a site-specific model-based nitrogen prescription, which takes long-term weather conditions into consideration. Both nitrogen prescriptions were evaluated based on corn grain yield, nitrogen use efficiency and economic aspects.

Materials and methods

Site description and overall design

The investigation on nitrogen management strategies was conducted over a three-year period (2006–2008) at Ihinger Hof experimental station (48°74`N; 8°93`E, altitude 450 m a.s.l.), University of Hohenheim, Germany. During the years 1976–2005 a mean annual precipitation of 694 mm, a mean temperature of 8.4°C and a mean daily solar radiation of 10.9 MJ m^{-2} was measured at the site. In 2006, the climate was characterized by slightly higher temperatures and more rainfall events compared to the mean; while in 2007, the area experienced a drier and warmer period at the beginning of the growing season. The year 2008 was characterized by a very wet growing season (Fig. 1).

The soil of the experimental site "Riech" is characterized as a heavy calcareous brown earth soils with high clay content (classified as silty clay and silty clay loam), see Fig. 2. The mean pH at the site was 7.2, the mean content of soil organic matter was 2.6%. The contents of phosphorous (32 mg P 100 g^{-1} soil), potassium (29 mg K

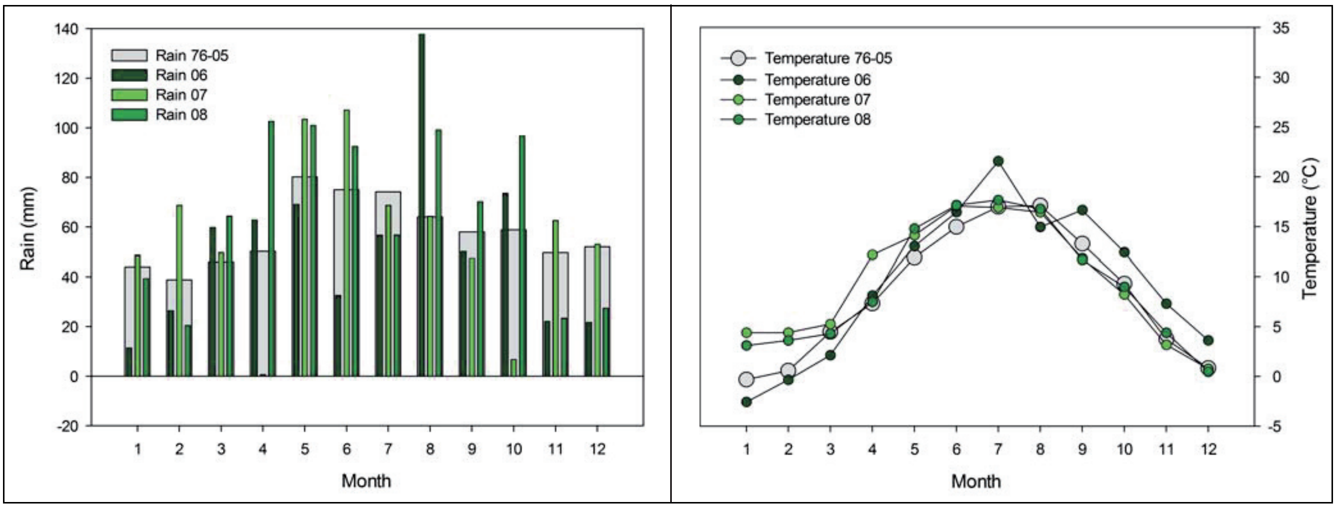

Fig. 1. **30-year (1976–2005) mean rainfall (left) and mean temperature (right) and the given weather in the experimental years 2006 (dark green), 2007 (light green), and 2008 (green) at the experimental station.**
30jähriges Mittel (1976–2005) für Niederschlag (links) und Temperatur (rechts), sowie das Wetter auf der Versuchsstation in den Jahren 2006 (dunkelgrün), 2007 (hellgrün) und 2008 (grün).

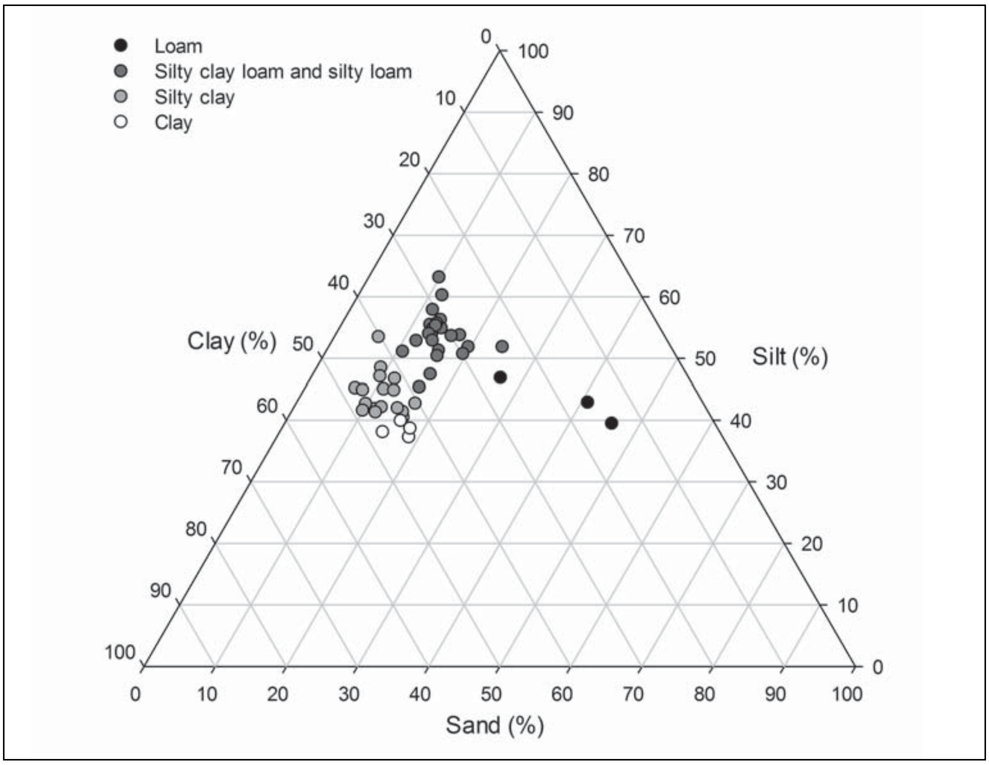

Fig. 2. **Soil texture determined in 48 management units (grids) at experimental site "Riech".**
Erfasste Bodentextur in den 48 Managementeinheiten (Grids) des untersuchten Schlags „Riech".

100 g^{-1} soil), magnesium (22 mg Mg 100 g^{-1} soil) in the soil were above the optimum content class C defined by VDLUFA standards (Kerschberger et al., 1997; Baumgärtel et al., 1999; Landwirtschaftskammer Nordrhein-Westfalen, 2012). This means the availability of those nutrients was sufficient and did not require additional fertilizer applications. The content of boron (0.5 mg B 100 g^{-1} soil) was within the optimum content class C (Landwirtschaftskammer Nordrhein-Westfalen, 2011).

Experimental design and agronomic management

Field trials for agricultural purposes are usually set up in small plot tests to ensure homogeneous soil conditions (Wagner and Prediger, 1989). But the spatial heterogeneity is one factor investigated in precision farming trials; therefore field trials in precision farming are normally designed on large heterogeneous sites, considering the soil condition as an additional factor.

Based on the working width of the farm machinery, the experimental site was separated virtually in single management units (grids) with a size of 36 × 36 meters (1296 m^2). The data collection was based on the determined management units. Soil samples for texture analyses were sampled in every management unit in three sampling depths (0–0.3 m, 0.3–0.6 m and 0.6–0.9 m). The texture analysis was based on the methods described by VDLUFA (1991). For the comparison of nitrogen management strategies, management units (1,296 m^2) were split into two grids: a control treatment with a grid area of 432 m^2 (12 × 12 m), and a model-based treatment with a grid area of 864 m^2 (24 × 36 m). The nitrogen application was performed with a pneumatic fertilizer spreader (Rauch Aero 1112, Sinzheim, Germany) with a spreading width of 12 m. The arrangement of control and model-based treatment was random within each row of management units (Fig. 3). In order to avoid blending effects at the border of the management units, a distance of ten meters between each management unit was omitted for data analysis.

Nitrogen management

Two different nitrogen management strategies were investigated in this experiment: a control treatment with a uniform application rate as well as a model-based treatment with a site-specific nitrogen application rate in each grid.

Mineral nitrogen was broadcast in both treatments as split application with the first application before seeding and the second application around 4th leaf stage (BBCH 14 or Zadoks stage 14; Zadoks et al., 1974). At the first application 30 kg N ha^{-1} calcium ammonium nitrate (CAN) was broadcast, at the second application urea was applied. The fertilizer spreader was controlled by a geo-referenced nitrogen application map to ensure and document the given amounts of nitrogen for each treatment and each management grid. Thus, the nitrogen application was performed offline as a mapping approach (Auernhammer, 2001).

The first nitrogen application rate of 30 kg N ha^{-1} was broadcast uniformly for all grids within the site before seeding. For the second nitrogen application in the control treatment, a nitrogen application rate of 130 kg N ha^{-1} was broadcast, according to the current farmer's practice, disregarding existing heterogeneity within the site. In the site-specific treatment a model-based nitrogen

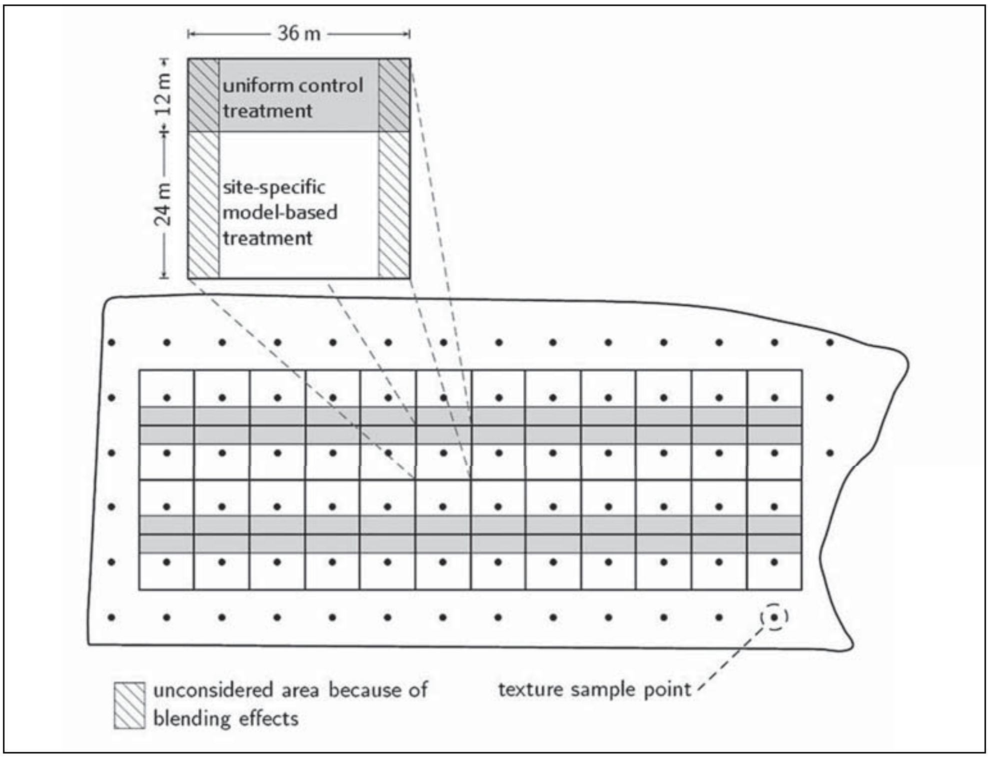

Fig. 3. Layout of the experimental design used for comparison of a uniform (control) and a site-specific (model-based) nitrogen management strategy in 48 management units (grids).
Anlage des Versuchsdesigns mit 48 Managementeinheiten (Grids) zum Vergleich der einheitlichen (Kontrolle) und der teilflächenspezifischen (Modell-basierten) Stickstoffmanagement-Strategie.

application was broadcast, ranging from 100–210 kg N ha^{-1} for single management grids (Fig. 4).

The site-specific model-based nitrogen prescription, which takes the long-term weather conditions into consideration, was developed with the crop growth model APOLLO (Batchelor et al., 2004). This process-oriented crop growth model calculates crop growth and development on a daily basis under consideration of current local conditions. Thus, grid and site based information, such as soil characteristics, weather, cultivar, management and historical yield data were used to calibrate the model for all grids within each site. During the calibration process, adjustments were made to selected soil properties to minimize the root mean square error (RMSE) between simulated and measured historical yield in all grids. Validation was performed by running the model for an independent season and comparing simulated and measured spatial yield, obtaining convincing results for the corn sites. For details and results on the model validation see Link et al. (2006c).

To develop the nitrogen prescription, the calibrated model was run for different nitrogen rates (0–200 kg N ha^{-1} in increments of 10 kg) for each grid and for 30 different years of historical weather data (1976–2005) to generate information about the range of yield potential within the site over the long-term. The optimum site-specific nitrogen prescription for the three-year period was computed by maximizing marginal net return (MNR) in each grid within the site by the following equation (1):

$$MNR_{n,t} = Y_{n,t}\, P_W - N_{n,t}\, P_N$$

where $MNR_{n,t}$ is net return (€ ha^{-1}) for grid n and year t, $Y_{n,t}$ is corn yield (kg ha^{-1}), P_W is the price of corn (0.10 € kg^{-1}), $N_{n,t}$ is the N application rate (kg N ha^{-1}), P_N is the price of nitrogen fertilizer (0.50 € kg^{-1}). Note that the computed optimum nitrogen rate depended on the chosen fertilizer and corn prices, as well as on the underlying weather data. In this study the historical weather data from 1976–2005 were taken into account.

Agronomic management

The site was ploughed (0.25 m) in autumn after the harvest of the previous crop corn. Seedbed preparation was done using a harrow in combination with a land packer. Corn (*Zea mays* L., cultivar 'Companero') was planted around end of April in all three years, the seeding rate was 9.5 kernels m^{-2} and the row distance was 0.75 m. Nitrogen management was performed as mentioned above. Pesticides were broadcast at relevant stages based on farmer's decision.

Data collection

Within each management grid, a data collection point (Fig. 3) was established for the control and the model-based nitrogen treatment. Over the three-year period, soil sampling for soil mineral nitrogen (N_{min}) was conducted before the vegetation period and after harvest at all sampling points. In order to calculate N_{min} (kg N ha^{-1}), both nitrate and ammonium were analysed with a FIAstar 5012 Analyser (FOSS Tecator, Sweden). During the vegetation period around 4^{th} leaf stage (BBCH 14 or Zadoks stage 14), flowering (BBCH 65 or Zadoks stage 60–65) and maturity (BBCH 90 or Zadoks stage 90–93) (Zadoks et al., 1974) plant sampling for biomass and yield were performed at 40 selected sampling points, representing the control and model-based nitrogen treatment for different soil characteristics within the site. At the selected sampling points plastic tubes were installed in a depth of 0–0.9 m to measure the soil moisture content with a

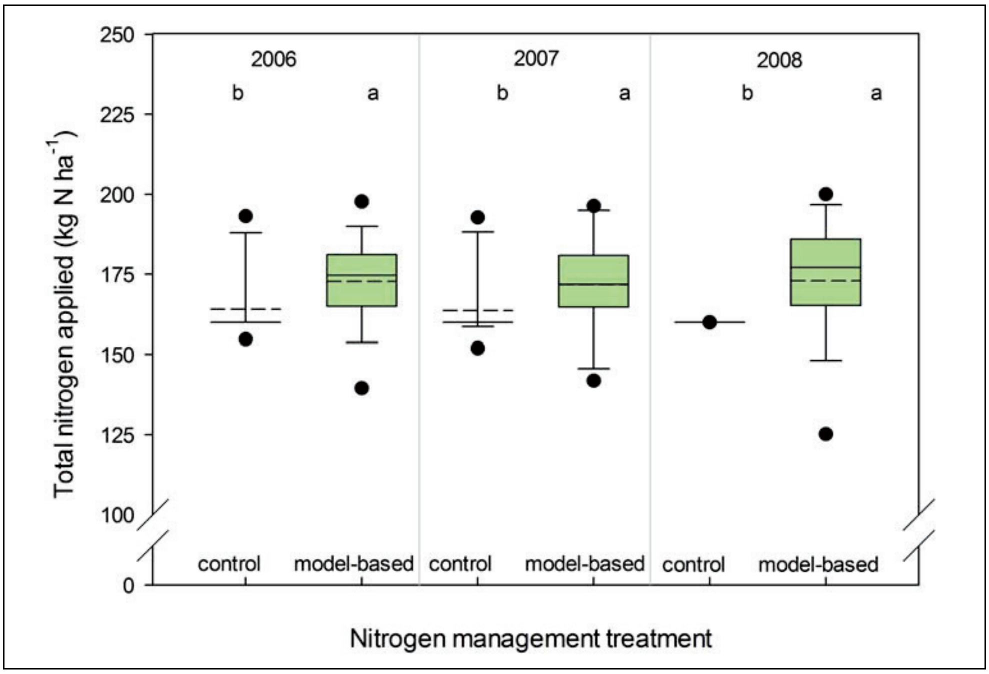

Fig. 4. Measured amount of nitrogen applied (kg N ha^{-1}) in uniform (control) and site-specific (model-based) nitrogen treatment in investigated years 2006, 2007, and 2008 (--- document mean N applied, whiskers document the 5^{th} and 95^{th} percentile).
Erfasste Stickstoffgabe (kg N ha^{-1}) der einheitlichen (Kontrolle) und der teilflächenspezifischen (Modell-basierten) Variante in den Jahren 2006, 2007 und 2008 (--- zeigen die mittlere Stickstoffgabe, Antennen zeigen das 5. und 95. Perzentil).

portable moisture measurement instrument (Trime FM, IMKO, Ettlingen, Germany) in a 14-day interval over the growing season.

For data analysis, collected data were differentiated in control and model-based nitrogen treatment and also categorized based on the underlying soil type. For this purpose, the four texture categories (TC), described in Tab. 1, were distinguished. After the growing season, nitrogen use efficiency (kg grain kg^{-1} N available) was determined for both nitrogen management strategies in all management grids. The amount of N available (kg N ha^{-1}) was calculated for each sampling point on the following equation (2):

$$N_{avail} = N_{min} + N_{fert}$$

with N_{min} = soil mineral nitrogen (kg N ha^{-1}) before vegetation period in the management unit and N_{fert} = grid specific total nitrogen application rate (kg N ha^{-1}). The calculation of nitrogen use efficiency was based on the equation described by Moll et al. (1982), which defines NUE as the quotient of grain weight and nitrogen supply (equation 3):

$$NUE\ (kg\ grain\ kg^{-1}\ N_{avail}) = yield\ (kg\ grain\ ha^{-1}) / N_{avail}\ (kg\ N\ ha^{-1})$$

The net return (€ ha^{-1}) was calculated for all management grids to evaluate the different nitrogen management strategies over the three-year period on an economic basis.

Data analysis

Statistical analysis for effect of nitrogen management strategy and effect of soil category on yield, nitrogen use efficiency and economic aspects was performed using the general procedures of Sigma Stat 3.5 (Jandel Scientific, San Rafael, CA, USA). Statistical differences are indicated by analysis of variance (ANOVA) using the Tukey test at the $\alpha = 0.05$ probability level.

Results and discussion

N application

The measured median and mean nitrogen application rates for each year are shown for the control and the model-based nitrogen treatment in Fig. 4. For some grids the measured nitrogen application rate deviated from the given nitrogen application rate in the geo-referenced nitrogen application map. These inaccuracies might be caused by delay in response time of the spreader during fertilizer application. Thus, the mean nitrogen application rate in the control treatment was 163 kg N ha^{-1} (instead of 160 kg N ha^{-1}), while in the model-based nitrogen treatment 173 kg N ha^{-1} were applied (Fig. 4). Hence, on average 6.1% more nitrogen was applied in the model-based treatment and this was statically significant. Moreover, in the model-based nitrogen treatment 73.6% of the grids achieved higher nitrogen application rates compared to the control treatment, whilst 26.4% of the grids achieved lower nitrogen application rates.

As shown in Fig. 5 the simulated optimum nitrogen application rate for each grid in the site-specific model-based nitrogen treatment was mainly driven by simulation of soil available water in each grid ($R^2 = 0.47$).

Also the model intern parameter for water availability correlates with the site-specific nitrogen application rate (kg N ha^{-1}) over all investigated years ($R^2 = 0.51$), showing that the more water that was expected to be available in a management grid, the higher the simulated nitrogen application rate for this grid (data not shown).

The measured amount of available water during the growing season was mainly influenced by content of silt ($R^2 = 0.65$). This is consistent with the knowledge that soil texture has a direct impact on water availability in a field (Scheffer and Schachtschabel, 1989; Ehlers and Goss, 2003) and is considered by the authors Shahandeh et al. (2005) for an easy development of site-specific nitrogen prescriptions, as soil texture is easy to measure and consistent over time.

The fact that the model-based nitrogen prescription was mainly driven by soil available water in the site is also in line with results of Miao et al. (2007), who stressed that the optimum site-specific nitrogen rate in corn strongly depends on current weather conditions in each growing season. Thus, when calculating the site-specific nitrogen management, not only the maximum net return over the long-term should be considered (as described in the materials and method section), more attention should be drawn to current weather conditions and thus, on the expected water availability within the actual growing season.

Tab. 1. Texture categories (TC), sorted by increasing fineness of texture
Texturkategorien (TC), sortiert nach ansteigendem Feinheitsgrad

Texture category (TC)	Soil type	Number of grids	Total number of grids	Total area of the site (%)
1	Loam (l)	3	**3**	**6.25**
2	Silty clay loam (sicl)	22	**24**	**50.00**
	/Silty loam (sil)	2		
3	Silty clay (sic)	17	**17**	**35.42**
4	Clay (c)	4	**4**	**8.33**

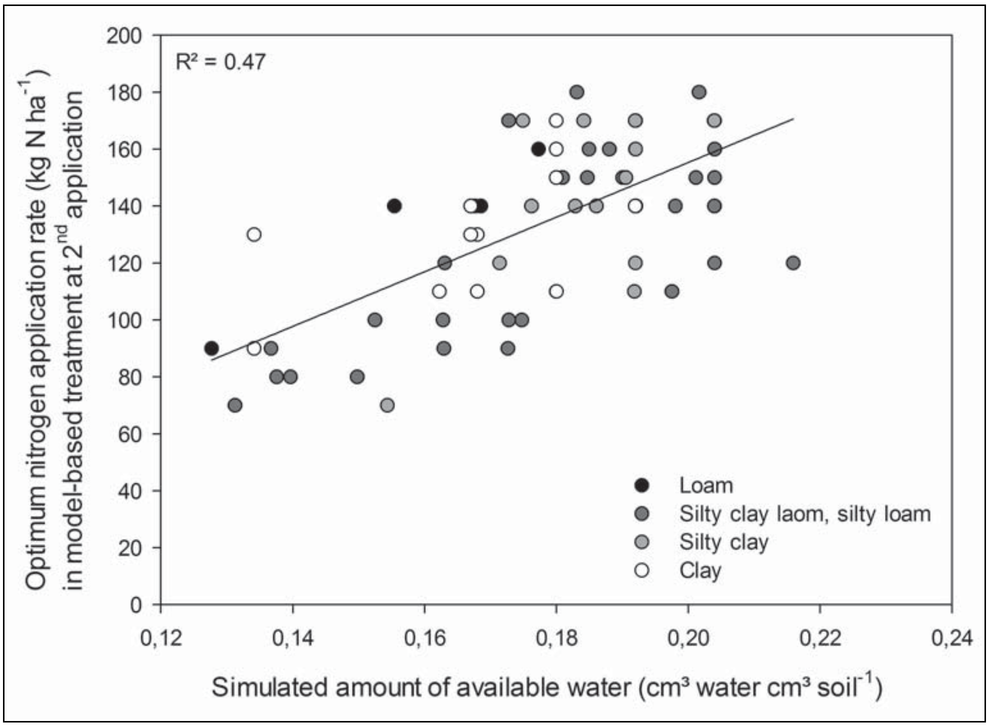

Fig. 5. Linear regression of simulated optimum nitrogen application rate (kg N ha^{-1}) against the simulated amount of water availability (cm^3 water cm^3 $soil^{-1}$) in the corresponding management grid.

Lineare Regression zwischen der simulierten optimalen Stickstoffapplikationsmenge (kg N ha^{-1}) und der simulierten Wasserverfügbarkeit (cm^3 Wasser cm^3 $Boden^{-1}$) in der jeweiligen Managementeinheit.

Tab. 2. Mean values of the investigated parameters nitrogen available, corn grain yield, nitrogen use efficiency and marginal net return. The parameters are categorized by treatment, texture category and year (Means marked with different letters are significantly different at p < 0.05)

Mittelwerte der untersuchten Parameter verfügbarer Stickstoff, Kornertrag, Stickstoffnutzungseffizienz und Nettoertrag. Die Parameter sind nach Behandlung, Texturkategorie und Jahr geordnet (Unterschiedliche Buchstabend kennzeichnen signifikante Mittelwertunterschiede bei p < 0,05)

	Nitrogen available (kg N ha^{-1})	Corn grain yield (kg ha^{-1})	Nitrogen use efficiency (kg yield kg^{-1} N available)	Marginal net return (€ ha^{-1})
Treatment				
Control	17.6 b	5877 b	33.5 n.s.	506.4 b
Model-based	187.2 a	6382 a	34.4 n.s.	552.0 a
Texture category (TC)				
1	179.5 n.s.	7051 a	39.7 a	621.3 a
2	178.2 n.s.	6032 b	34.0 b	512.0 b
3	185.3 n.s.	6023 b	32.6 b	517.8 b
4	185.5 n.s.	6494 ab	34.9 ab	563.8 ab
Year				
2006	183.6 n.s.	5245 c	28.8 c	440.2 c
2007	181.7 n.s.	7407 a	40.8 a	656.8 a
2008	178.7 n.s.	5686 b	31.9 b	485.3 b
Total	167.6	6130	33.9	529.2

Grain yield

The mean grain yield of the investigated field was strongly influenced by the year (Tab. 2), indicating a distinct influence being from the weather conditions. Despite differences in mean grain yield over the years, a significant stability in yield pattern was given between the years 2007 and 2008 for both control and model-based treated grids (Tab. 3). These results are similar to findings of LINK et al. (2006b) and PING and DOBERMANN (2003), who showed that the size of the management grids needs to

Tab. 3. Pearson correlation coefficient (r) of grid based corn grain yields in year 2006, 2007, and 2008 (* = significant at p < 0.05)
Pearson Korrelationskoeffizienten (r) zwischen Grid-basierten Kornerträgen in den Jahren 2006, 2007 und 2008 (= signifikant bei p < 0.05)*

	Corn grain yield 2007 (kg ha⁻¹)	Corn grain yield 2008 (kg ha⁻¹)
Corn grain yield 2006 (kg ha⁻¹)		
Control treatment	0.300*	0.390*
Model-based treatment	0.320*	0.438*
Total site	0.282*	0.363*
Corn grain yield 2007 (kg ha⁻¹)		
Control treatment		0.908*
Model-based treatment		0.853*
Total site		0.892*

catch the size of the underlying yield limiting factors to adequately describe temporal yield stability. Then management grids could be used to create larger and continuous yield classes over time. The determination of yield classes by geostatistical methods can serve as a tool to delineate management zones for site-specific applications (MILNE et al., 2012).

Significant differences in grain yields between nitrogen treatments were not found in all investigated years (Fig. 6). In 2006, the control treatment resulted in slightly higher grain yields compared to the model-based treatment (5,436 and 5,332 kg ha^{-1}, respectively, $P < 0.01$), in 2007 and 2008 the situation was contrariwise (6,925 and 7,903 kg ha^{-1}, n.s.; 5,374 and 6,015 kg ha^{-1}, $P < 0.05$). Over the three-year period, the mean grain yield in the control nitrogen treatment (6,183 kg ha^{-1}) was significantly lower than in the model-based nitrogen treatment (6,749 kg ha^{-1}, the difference of means was 566 kg ha^{-1}, $P < 0.05$). This was, on the one hand, caused by the distinct although not significantly different mean values in grain yield between control and model-based nitrogen treatment in 2007. On the other hand, it might have been due to the fact that across all three years, the mean nitrogen application rate was about 6% lower in the control treatment compared to the model-based treatment. The tendency of slightly higher corn yields in site-specific nitrogen treatment compared to a uniform treatment was also found in other studies (KOCH et al., 2004; MIAO et al., 2007) indicating that site-specific nitrogen application fit the nitrogen demand of the plant. Also, concerning soil category (SC), significant differences were determined in corn grain yield over the three-year period. Over the whole site in loam management units (TC1), significantly higher grain yields were reached when compared to silty clay loam and silty loam (TC2) and silty clay (TC3) management units (Tab. 2). As TC1 represents a loamy soil, which is well known as a highly productive soil type (EHLERS and GOSS, 2003), this result corroborates the expectations.

For corn grain yield, there was no statistically significant interaction between year and nitrogen treatment ($P = 0.24$), year and TC ($P = 0.10$) or nitrogen treatment and TC ($P = 0.46$) (data not shown). The comparison of control and model-based nitrogen treatment within TCs indicated significant differences within silty clay loam and silty loam (TC 2) only. Here, the control treatment resulted in significantly lower grain yields when compared to the model-based nitrogen treatment (5,679 kg ha^{-1} and 6,434 kg ha^{-1}, $P < 0.05$). This indicates that on silty clay loam and silty loamy soil, the soils with the

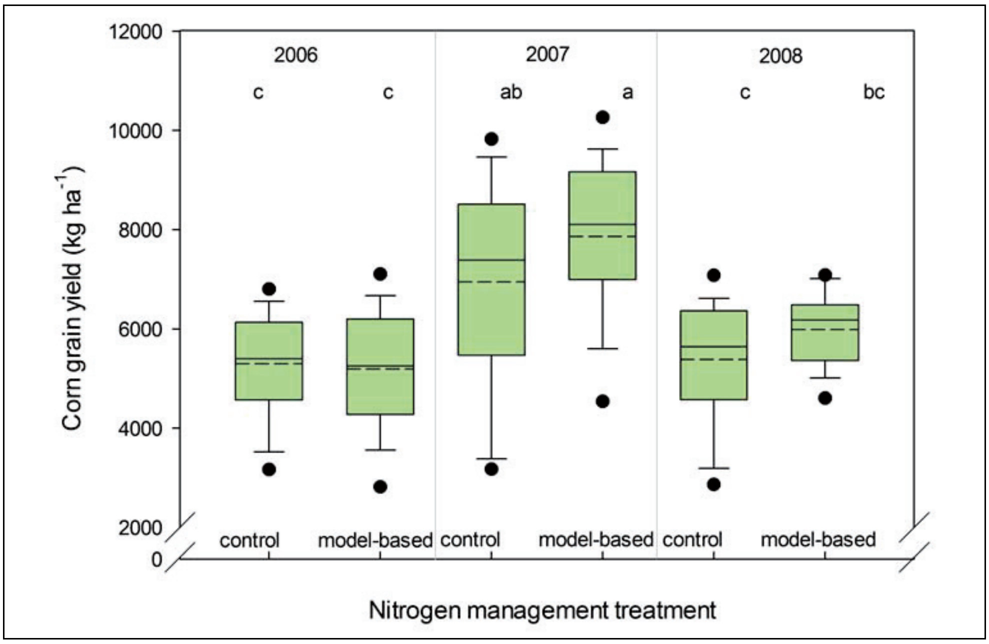

Fig. 6. Corn grain yields (kg ha⁻¹) in uniform (control) and site-specific (model-based) nitrogen treatment in investigated years 2006, 2007, and 2008 (--- document mean corn grain yield, whiskers document the 5th and 95th percentile).
Kornertrag (kg N ha⁻¹) der einheitlichen (Kontrolle) und der teilflächenspezifischen (Modell-basierten) Variante in den Jahren 2006, 2007 und 2008 (--- zeigen den mittleren Kornertrag, Antennen zeigen das 5. und 95. Perzentil).

highest amount of available water (Ehlers and Goss, 2003), the uniform nitrogen application rate was not adequate for corn plants.

However, for both nitrogen treatments only a slight correlation between corn grain yields and nitrogen application rate could be determined over all three years (data not shown). Also, between grain yields and nitrogen availability no strong correlations were obvious (data not shown). These results indicate that except for silty clay loams and silty loamy soil, nitrogen application rate and also nitrogen availability were not the main driving factor for corn grain yields. This is similar to the results of Scharf et al. (2006), who found that optimal nitrogen rates were seldom directly related to yield variability. They concluded that other factors as soil nitrogen supply, like in-season nitrogen loss and nitrogen uptake efficiency, also may play an important role for existing yield variability. Besides nitrogen, other nutrients such as P (Wiedenfeld and Provin, 2010), K, Mg are also described as major yield limiting factors in corn. Subedi and Ma (2009) identified weed infestation as a major yield limiting factor, followed by nutrient supply and seeding rate.

As described in the literature (Oberle and Keeney, 1990; Norwood, 2000; Calviño et al., 2003; Schmidt et al., 2011), water was considered as one of the most yield driving factors for corn yield; especially in dry seasons. However, in none of the investigated years, a significant correlation between measured soil moisture and grain yield could be determined. While in 2006 and 2008 the rainfall seems to be sufficient, in 2007 a very dry period at the beginning of the growing season was determined. The fact that soil moisture was not measured continuously, but only at a 14-day interval over the vegetation period, might be a reason that also in dry seasons these measurements seem to be of limited explanatory power for grain yield variability.

Nitrogen use efficiency

The nitrogen use efficiency (kg grain kg^{-1} N available) was mainly influenced by year and soil category, but not by nitrogen treatment.

In year 2007, nitrogen use efficiency was significantly higher (40.81 kg grain kg^{-1} N available) when compared to 2006 (29.48 kg grain kg^{-1} N available) and 2008 (31.81 kg yield kg^{-1} N available), respectively. A significant difference in nitrogen use efficiency could not be determined between control and model-based nitrogen treatment in any year. Also in 2007, the mean nitrogen use efficiency of the model-based nitrogen treatment was higher when compared to the control nitrogen treatment (39.14 and 42.47 kg grain kg^{-1} N available); however the difference was not significant (Fig. 7). With regard to nitrogen use efficiency, no significant advantage of either one of the nitrogen management strategies was visible. However, a lower range in nitrogen use efficiency of the model-based nitrogen treatment compared to the uniform control treatment was visible in 2007 and 2008 (Fig. 7). Against the background that no significant differences in straw and grain nitrogen content was visible in 2006 and 2007 (data not shown) and in 2008 significantly higher nitrogen content in straw and grain were determined in the model-based treatment (straw: 0.65%; grain: 1.44%) compared to the control treatment (straw: 0.61%; grain: 1.24%), an adequate supply of corn plants in the site-specific nitrogen treatment was achieved.

Over the three-year period, the highest nitrogen use efficiency was determined in grids belonging to loamy grids (TC 1: 42.10 kg grain kg^{-1} N available), the lowest efficiency in silty clay grids (TC 3: 32.80 kg yield kg^{-1} N available). In grids with silty clay loam and silty loam soils (TC 2) and clay soil (TC 4) about the same nitrogen use efficiency with 34.03 and 34.93 kg grain kg^{-1} N available, respectively, was reached. Thus, in this study the

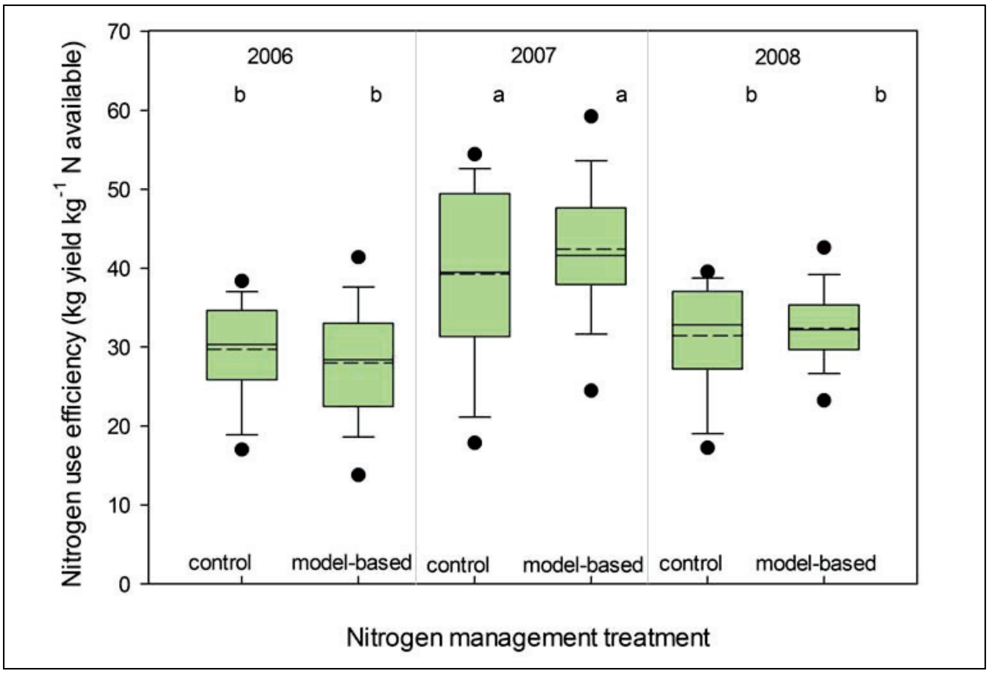

Fig. 7. Nitrogen use efficiency (kg yield kg^{-1} N available) in uniform (control) and site-specific (model-based) nitrogen treatment in investigated years 2006, 2007, and 2008 (--- document mean nitrogen use efficiency, whiskers document the 5th and 95th percentile).
Stickstoffnutzungseffizienz (kg Ertrag kg^{-1} verfügbarem N) der einheitlichen (Kontrolle) und der teilflächenspezifischen (Modell-basierten) Variante in den Jahren 2006, 2007 und 2008 (--- zeigen die mittlere Stickstoffnutzungseffizienz, Antennen zeigen das 5. und 95. Perzentil).

nitrogen use efficiency was not directly affected by the underlying soil type.

However, a dependency between measured soil moisture content and nitrogen use efficiency could be shown around BBCH 87 ($R^2 = 0.49$) in 2007, and around BBCH 30 ($R^2 = 0.30$) and 50 ($R^2 = 0.63$) in 2008. In 2006, a correlation was found between nitrogen use efficiency and nitrogen application rate ($R^2 = 0.27$), mainly driven by varying nitrogen rate in the site-specific nitrogen treatment. These results indicate that both nitrogen, and water availability effect nitrogen use efficiency in corn.

Economic aspects

The calculated net return (€ ha^{-1}) indicated significant differences between both nitrogen management strategies.

The highest net return over the whole site was achieved in 2007 (701 € ha^{-1}), while in 2006 and 2008, the net return was significantly lower (475 and 511 € ha^{-1}, respectively). In 2007 and 2008 a slightly higher net return was realized in model-based nitrogen treatment compared to the control treatment, but the differences were not statistically significant (Fig. 8). However, over the three-year period a significant difference between both nitrogen management strategies was visible (Tab. 2), indicating a higher net return for the model-based nitrogen treatment. Over all years in about 61% of the management grids higher net returns were achieved with model-based nitrogen treatment.

The highest net return was achieved on loam soils (TC1), independent of the investigated year. In 2006, silty clay loam and silty loam soils (TC2) experienced the lowest net return, while in 2007 and 2008, silty clay soils (TC3) showed the lowest net return. Over the years and the TC, most of the site-specifically treated grids achieved a higher net return than uniformly treated grids (see section N application).

From solely assessing economic input and output (as described in eq. 1), the site-specific nitrogen management seems to therefore be beneficial, especially with regards to high yielding loamy soils. However, for the full statement of the facts, it is important to also state other costs, which are associated with the development of site-specific nitrogen prescriptions (data gathering, model development, and working hours) as well as machinery. Several authors (Babcock and Pautsch, 1998; Thrikawala et al., 1999; Liu et al., 2006) describe the cost associated with site-specific management, and most results indicate that the profitability of site-specific management depends on factors such as current management system, heterogeneity of soil conditions, crop, variety, etc. Hence, for a final evaluation of economic feasibility of site-specific nitrogen application, many aspects other than purely assessing input and output factors need to be taken into account.

Conclusion

During the three-year period of investigation, no significant correlation between nitrogen application rate and corn grain yield was found, indicating that nitrogen was not the main driving factor for grain yield in this study. However, weak correlations between grain yield and soil category were found; but neither nitrogen nor soil category could explain yield variability within the site sufficiently. These findings are contrary to studies by other authors, who indicated soil water content and nutrients as major yield limiting factors. The investigation of pH, available content of P, K, Ca, Mg, soil organic

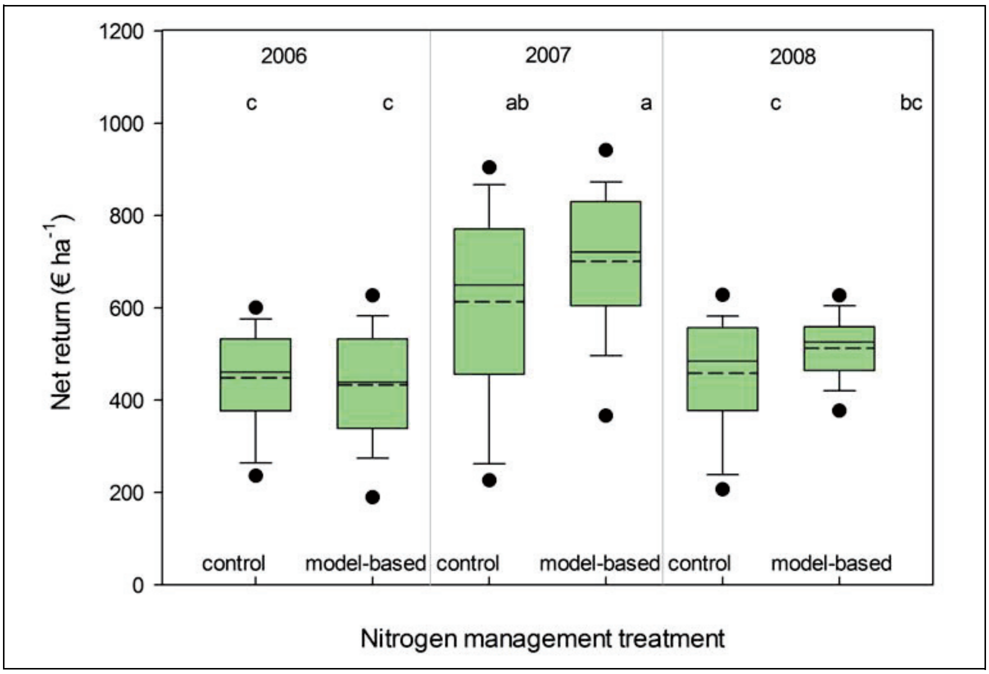

Fig. 8. Net return (€ ha^{-1}) in uniform (control) and site-specific (model-based) nitrogen treatment in investigated years 2006, 2007, and 2008 (--- document mean net return, whiskers document the 5th and 95th percentile). *Nettoertrag (€ ha^{-1}) der einheitlichen (Kontrolle) und der teilflächenspezifischen (Modell-basierten) Variante in den Jahren 2006, 2007 und 2008 (--- zeigen den mittleren Nettoertrag, Antennen zeigen das 5. und 95. Perzentil).*

matter on the field level indicated sufficient nutrient supply, but for further studies also the variability of these nutrients within the field should be taken into consideration as it may explain the given variations in grain yield.

Concerning nitrogen use efficiency, no significant advantage of either one of the nitrogen management strategies was visible. The results indicate, however, that nitrogen use efficiency was mainly driven by nitrogen application rate and water availability in this field. The measured nitrogen content in straw and grain together with a lower range in nitrogen use efficiency for the model-based site-specific nitrogen treatment may point at an adequate nitrogen supply of corn plants across the site in the site-specific nitrogen treatment.

A similar picture was given for both nitrogen strategies concerning the economic aspect. Thus, neither of the nitrogen management strategies was superior when considering the selected criteria: corn grain yield, nitrogen use efficiency and net return. The situation may differ when focusing more on environmental aspects, and looking for example at nitrogen leaching potential of both strategies.

The model-based nitrogen prescriptions showed nonetheless a positive correlation to soil available water. Thus, the better the expected water availability in a grid, the higher the optimum nitrogen rate applied. Using this site-specific model-based strategy the nitrogen application rate was reduced compared to the control treatment in about 36% of the grids. Moreover, an over-fertilization of less productive areas on the site and the risk of nitrogen leaching have the potential to be avoided with the implementation of a site-specific model-based nitrogen treatment. On the other hand, areas of higher productivity (about 74% of the grids) did receive more nitrogen, and thus, do not run into the risk of yield losses due to under-fertilization of these areas. This result indicates that the implementation of APOLLO for calculating site-specific nitrogen prescription for corn production seems to be quite beneficial in terms of utilising an efficient method for nitrogen input. The results indicate that the model-based nitrogen management was mainly driven by simulated water availability. Consequently, great attention needs to be given to current weather conditions and the expected water availability within the current growing season, potentially increasing the additional value of implementing model-based nitrogen prescriptions.

Overall, a further study identifying yield driving factors and analysing environmental aspects is required to come to a final evaluation of uniform and model-based site-specific nitrogen prescription in corn.

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