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Evaluation and Improvement of N Fertilization Strategies in the Wheat / Maize Double-Cropping System of the North China Plain

Dissertation

submitted in fulfilment of the requirements for the Degree
„Doktor der Agrarwissenschaften“ (Dr. Sc. Agr.)

to the
Faculty of Agricultural Sciences

by
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2014

This thesis was accepted as a doctoral dissertation in fulfilment of the requirements for the degree „Doktor der Agrarwissenschaften“ (Dr. sc. Agr. / Ph.D. in Agricultural Sciences) by the Faculty of Agricultural Sciences at University of Hohenheim on the 15th of April 2014

Date of oral examination: 24th of June 2014

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standard abbreviations according to the International System of Units (SI) are used
chemical elements are abbreviated using their chemical symbol

AE _N	Agronomic Efficiency of Nitrogen
ANLG	Apparent net N loss or gain
ANM	Apparent net N mineralization
ASN	ammoniumsulphate nitrate
BMBF	Federal Ministry of Education and Research (Germany)
CAU	China Agricultural University
C _{org}	organic carbon
ETA	actual evapotranspiration
FP	farmers' practice
HY	high yield
MOST	Ministry of Science and Technology (China)
DCD	dicyandiamide
DMPP	3,5-dimethylpyrazolephosphate
DüV	Düngerverordnung (German regulation on the use of fertilizers)
IPCC	International Panel on Climate Change
MAE	mean absolute error
MBE	mean bias error
ME	modelling efficiency
MOST	Ministry of Science and Education (China)
nBPT	N-(n-butyl) thiophosphoric triamide
NCP	North China Plain
NFR	nitrogen fertilizer recommendation
NI	nitrification inhibitors
N _{min}	mineral nitrogen
NUE	nitrogen use efficiency
OECD	Organisation for Economic Development and Co-operation
PRC	People's Republic of China
RE _N	Recovery Efficiency of Nitrogen
SE	standard error
UAN	urea ammoniumnitrate
UI	urease inhibitor

1 General Introduction

1.1 Introduction

China, with a population of 1.4 billion, is currently the most populated country in the world and has seen an eventful 65 years since the founding of the People's Republic.

Since the 1980's, when the government introduced a more liberal approach to the system of socialism that was started 1949, the country has become one of the fastest developing economies in the world (Carter and Li, 1999). The standard of living has increased, mainly through the encouragement of entrepreneurship and a strong emphasis on the development of infrastructure, new technologies and the construction business (Liu and Diamond, 2005). By now, the image of China has become associated mainly with the high standard of living and with the development of the country's two major cities, Beijing and Shanghai.

It is easy to forget that, outside the cities, the rural areas of China are still highly dependent on the production of agricultural goods and that there is a wide gap in income between cities and rural areas (OECD, 2005).

In order to feed its continuously growing population, small scale farmers are called upon to meet the government's goal of self-

sufficiency. To facilitate and encourage agricultural production, the government has developed programs ranging from tax relief for farmers to subsidies on fertilizers and agrochemicals (Fan and Cohen, 1999). Agricultural production has increased strongly from the 1960's onward, mainly through the systematic construction of industrial plants for the synthesis of nitrogen fertilizers (Carter and Li, 1999).

This strong intensification of both the industrial and agricultural sectors has led to an ever increasing problem of environmental pollution (Liu and Diamond, 2005) and pictures of smoking chimneys and algal blooms in the Bay of Bohai have become just as common in the mind of people as pictures of high-rises and bicycles.

The use of fertilizers and agrochemicals has long overtaken the required dose and this over-application must be reduced should environmental pollution through agriculture be stopped (Zhao et al., 2007; Ju et al., 2009; Ti et al., 2012).

Within the framework of the Sino-German cooperation „Innovative Nitrogen Management Technologies to Improve Agricultural Production in Intensive Chinese Agriculture“ the China Agricultural University and the University of Hohenheim worked closely together in order to identify strategies for the improvement of agricultural production in the North China Plain, the main production area of cereal crops in China.

Aiming at the applicability of research, experiments in fields, greenhouses and laboratories were conducted in order to identify methods for the reduction of nitrogen (N) application and loss, and also

devise recommendations for farmers in the region and for decision makers in government.

The research presented here was carried out within the framework of this Sino-German cooperation, with the main objective of accurately describing the effect of N application in a common summer-maize/winter-wheat cropping system of the NCP, and to develop recommendations for a reduction of agricultural pollution from N fertilization.

1.2 The study area

The NCP is an alluvial flood plain that, depending on the definition, stretches from Beijing in the North to the Huai River in the south. The Shanxi Mountains form the western border of the plain, while the Yellow Sea and the East China Sea lie to the east. The Yellow River, on the deposits of which the NCP is based, flows through the NCP to the Bay of Bohai (figure 1).

This region is the main agricultural production area for cereal crops in China and is dominated by summer-maize/winter-wheat double cropping systems in the north, and rice/winter-wheat double cropping systems in the south.

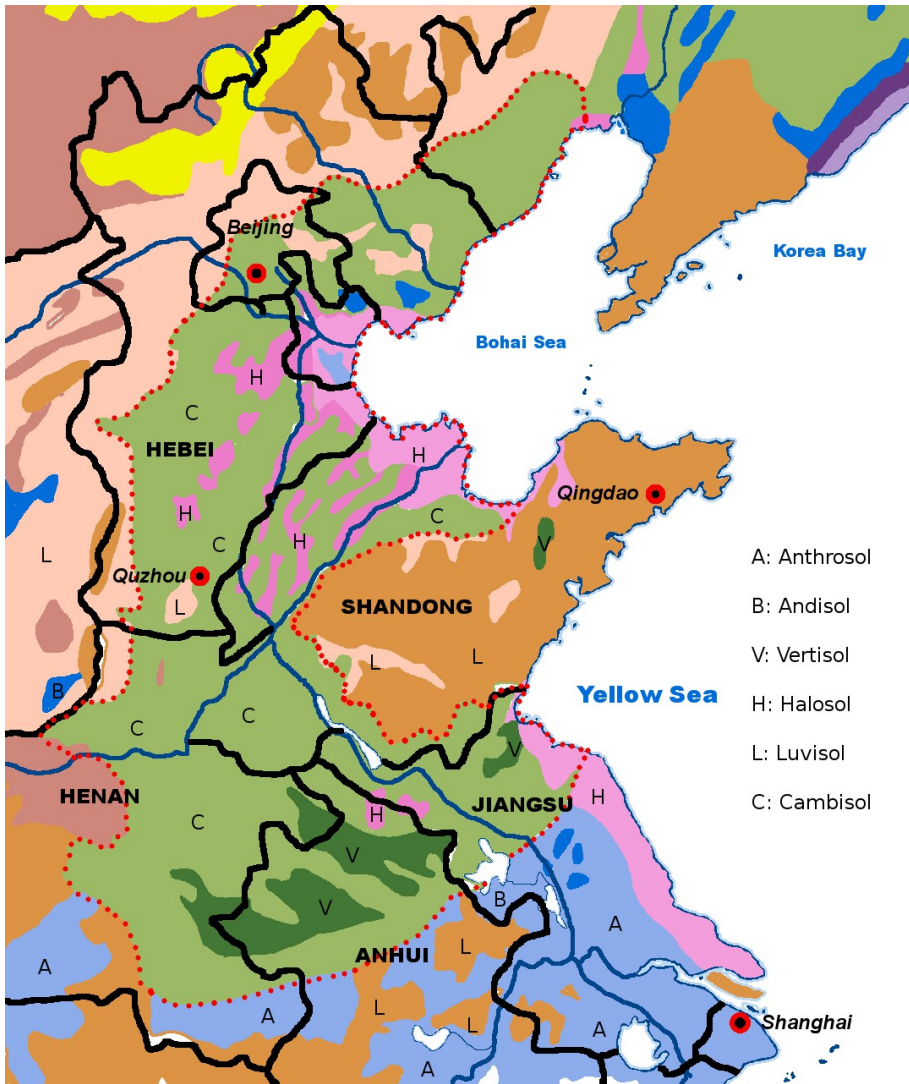


Figure 1: Provinces (marked by black lines) and soils of the North China Plain (marked by red line). The research area of this study, Quzhou County (red dot), is located in the south of Hebei Province (modified from Menegat, 2012 and Nanjing Institute of Soil Science: Soil Map of China).

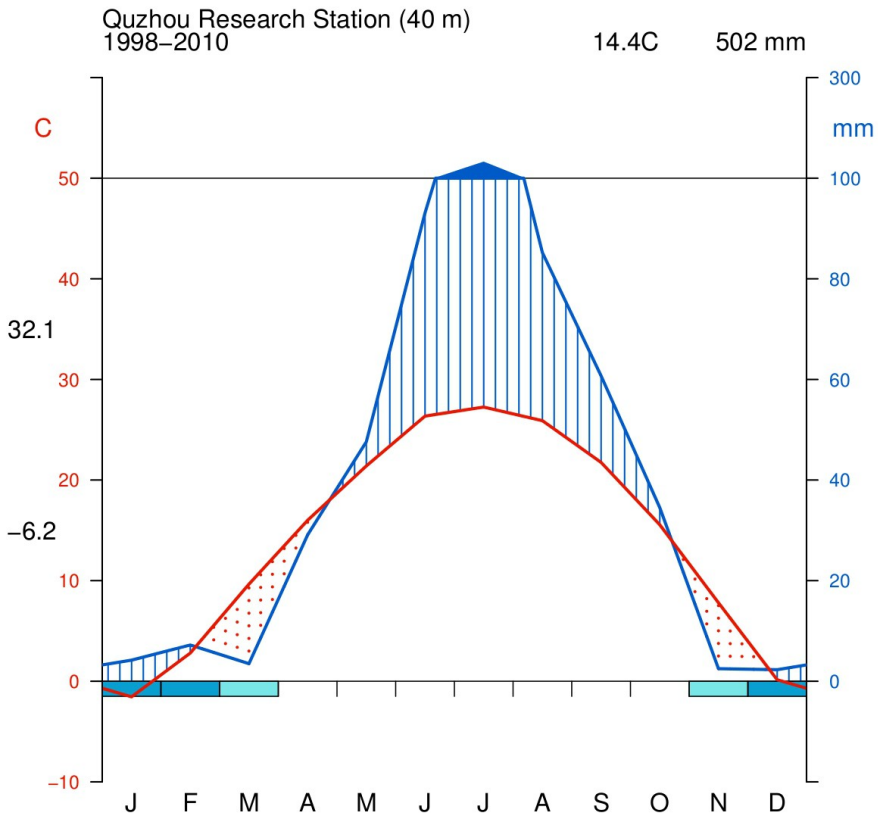


Figure 2: Walter/Lieth climate diagram for the experimental research station in Quzhou County the blue graph shows mean monthly precipitation, blue vertical lines indicate periods of high humidity. The red graph shows mean monthly temperature, red dots indicate prevailing arid conditions. Blue rectangles beneath the x-axis indicate when frost events are likely (data: Quzhou Research Station, CAU).

The research for this thesis was conducted in the vicinity of the CAU's experimental station in Quzhou County, Hebei Province (115 °E, 36 °N, 40 m a.s.l.). The closest city for transport by train is the city of Handan.

The soil in the research area can be classified as a Cambisol with a silt-loam texture (IUSS Working group WRB, 2007). The climate of the NCP follows a monsoon influenced steppe climate with a mean temperature of 13.6 °C and mean precipitation of 490 mm between 1980 and 2007. The climate data for the experimental station of Quzhou from 1998 to 2010 shows a mean temperature of 14.4 °C and mean precipitation of 502 mm (figure 2).

1.3 Agricultural practice in the NCP

The NCP is characterized by small-scale farms that are often considerably less than one hectare in size. These small fields are intensively cultivated, as they have been for centuries. In Quzhou county, the main cash crops are summer-maize and winter-wheat, which are grown in a double cropping system with a yearly cycle, and which are the subject of this thesis. Further, the area on which cotton-wool is produced is increasing. Other crops produced in the area are cereal crops such as sorghum as well as peanuts and assorted vegetables (personal observations).

The intensive cropping systems of the NCP, such as the summer-maize / winter-wheat cropping system of the research area, are reliant on the use of chemical N fertilizers, as there is a strong separation of arable- and livestock-farming (Schuchardt et al., 2011). The increased use of N

fertilizers at first led to a strong increase in agricultural production, but yields in the area have not increased in relation to increased fertilizer application since the 1980's (Ti et al., 2012).

The high application rates of N are reflected in the summer-maize/winter-wheat cropping systems of the Quzhou area, where a median of 550 kg N ha⁻¹ are applied, with a single application of 250 kg N ha⁻¹ to summer-maize and the application of 150 kg N ha⁻¹ each at sowing and re-greening of winter-wheat (= 300 kg N ha⁻¹), mainly in the form of urea (chapters II and III).

1.4 Problems associated with over-fertilization of N

Sprengel and Liebig's „Law of the Minimum“ (Mitscherlich, 1909) states that increased application of the most limiting plant nutrient leads to increased yields until another nutrient becomes the most limiting factor, after which yield remains constant at increased application rates of this nutrient.

After further research, Wollny (1897) realized that the yield of crops did not remain constant with increasing application rates, but were reduced once a certain rate of application was reached, thereby stating the „Law of the Optimum“.

In the case of N as a plant nutrient, the decline of yield is associated mainly with the increased storage of nitrate in the plant vacuoles,

leading to thinner cell walls that favor both plant diseases and the lodging of crops in the field, even though modern varieties of cereal crops are better suited to high application rates of N (Huber et al., 2012).

One of the main problems associated with the over-application of reactive N is the loss of these surpluses to the environment. Subbarao et al. (2006) summarized that N application above the optimum rate for yield development has no further influence on increased plant development, but is increasingly subjected to loss-pathways.

Processes of N transformation are constantly taking place in soils, mainly during the processes of mineralization and nitrification. The dominant form of N found in agricultural fields is NO_3^- , which is water soluble and therefore particularly prone to leaching when irrigation or precipitation favor a downward movement of water through the soil profile. The leaching of NO_3^- as well as surface run-off from agricultural fields is closely related to the eutrophication of ground and surface waters and strict regulations have been implemented in developed countries in order to reduce these processes (European Nitrates Directive, 1991; Düngeverordnung, 2006).

A major loss pathway of reactive N from agricultural fields is caused by the processes of nitrification and denitrification. During the turnover of reactive N species in soils gaseous forms of N, such as NH_3 , N_2 and N_2O are lost to the atmosphere. These loss pathways of N are an important factor in reducing the efficiency of fertilizer application and

the short and long range transport and deposition of N. Vittoušek et al. (1997) have described anthropogenic changes to the N cycle, stating that the negative effects of the deposition of nitric acid and ammonium contribute to global warming, a change of biodiversity and the acidification of surface waters.

N₂O is described as a climate relevant gas with a high stability, remaining in the atmosphere for up to 120 years, having a global warming potential 300 times as high as CO₂ (IPCC, 2001). Further, it has been calculated that a total of 13.5t CO₂-equivalents are lost during the production, transport and application of 1t chemical N fertilizer (Zhang et al., 2011).

1.5 Methods for reducing the loss of reactive N

It has been argued that emission and transport of reactive N species are contributing considerably to the N supply of agricultural crops in the NCP (Ju et al., 2009), with an annual N deposition of about 80 kg N ha⁻¹ (He et al., 2007). In combination with applied N fertilizers and the release or mineralization of N during the vegetation period, N-deposition is further increasing the N balance of arable crops, leading to an increasing cycle of over-application of N (Vittoušek et al., 1997).

In order to stop or reverse the negative effects of excessive N application it is necessary to reduce the surplus of N and thereby the

potential of loss.

Valid suggestions for the reduction of N loss from agriculture to the environment have been made (Raun et al., 1999; Lhada et al., 2005). Mid- to long-term goals are the breeding of more N efficient crops that are able to acquire more of the supplied N, thereby reducing the N surpluses in the field. While the breeding of such crops is a valid aim it does not address the input of N through farming operations. The short-term methods for the reduction of N loss, being the subject of this thesis, are the adjustment of N application rates to crop requirements, aiming to reduce the N surplus after harvest and the development of stabilized N fertilizers and innovative application techniques that reduce the risk of N loss.

The adjustment of N application rates to meet crop demands firstly involves estimating the expected yield range of crops and the N content of the harvested produce. Secondly, the determination of soil mineral N (N_{\min}) before fertilization is necessary. The difference between crop N requirement and N_{\min} is regarded as the optimum N rate for the expected yield level (Wehrmann and Scharpf, 1979).

Measures for stabilizing chemical N fertilizers aim at reducing the loss of N after application. These methods concentrate mainly on ammonium-based fertilizers and urea, as ammonium binds to negative colloid-surfaces of soil particles and is thereby usually less affected by the loss-pathways of leaching and gaseous emission.

The stabilization of these N fertilizers can be achieved either through a

banded, sub-surface application of ammonium based fertilizers such as urea ammonium nitrate (UAN), ammoniumsulphate nitrate (ASN) or urea. The concentrated application of these N sources inhibits the process of nitrification through ammonium-concentrations that act toxic for nitrifying bacteria, thereby retaining N in the ammoniacal form and reducing leaching and gaseous losses of N (Sommer and Jensen, 1994; Lhada et al., 2005).

Nitrification may also be inhibited through active chemicals such as dicyandiamide (DCD) or 3,5-dimethylpyrazolephosphate (DMPP). These chemicals inhibit the first step of nitrification catalyzed by *nitrosomonas* bacteria. Research has shown that these nitrification inhibitors (NI) may increase the efficiency of N fertilizers and further reduce the gaseous emission of N₂O (Ruser et al., 2012; Pfab et al., 2012).

The down-side of retaining N fertilizers in the ammoniacal form is the increased potential of ammonia volatilization when these fertilizers are applied to fields with a pH of above 7, as the dissociation balance between ammonium and ammonia is shifted towards the more volatile molecule. The loss of ammonia from N fertilizer poses a significant problem in the NCP, where urea is the dominant form of N fertilizer used. The percentage of N loss per applied N lies somewhere in the area between 2.5% over a 30 day period and 30 percent after a 3 day period (McKinnes et al., 1986; Sommer and Jensen, 1994; Zhang et al., 2011) and it has been estimated that 95 % of N loss in China occurs in the

form of ammonia volatilization after the application of urea or ammonium bicarbonate (Yan et al., 2003).

In areas with alkaline soils such as the NCP, the use of NI may therefore be contra-productive, as the retention of ammonium may increase the potential for ammonia loss. It may, therefore, be more desirable to stabilize the widely used N form of urea by inhibiting the function of the urease enzyme, which catalyzes the hydrolysis of urea.

An effective chemical that inhibits the function of the urease enzyme is N-(n-butyl) thiophosphoric triamide (nBPT), which has been shown to reduce the loss of ammonia and thereby increase the efficiency of urea-based fertilizers on a variety of crops (Watson et al., 1990; Kawakami et al., 2012, Rodrigues Soares et al., 2012).

1.6 Aims and objectives

The aim of this study was to evaluate strategies for the reduction of N application in a wheat / maize double-cropping system of the NCP and to identify methods for the reduction of N loss in intensive agriculture in China. The objectives of this research were:

(1) to apply an N_{\min} based approach for the calculation of N application rates to a previously over-fertilized farmer's field of the NCP and to evaluate the potential of reducing N inputs while maintaining the grain

yield of the double-cropping system;

to evaluate fertilizer strategies aiming to reduce N inputs and loss and evaluate their effect on fertilizer N use, grain yields and N use efficiency.

(2) To evaluate the impact of reduced N application on N balance in a farmer's field and on the dynamics of N in the intensive wheat / maize double-cropping system.

(3) to calibrate and validate a crop-growth simulation model (HERMES) for the conditions of the NCP and to identify fertilizer and irrigation strategies that may lead to a reduction of fertilizer N inputs and losses of N from an intensive wheat / maize cropping system.

(4) to assess whether a simplified recommendation for fertilizer N application that takes crop requirements, N dynamics and the technical capabilities of small-scale farmers into account, may reduce N inputs in the NCP while securing the yield of a wheat / maize double cropping-system.

(5) to evaluate the potential of reducing N loss from urea in the form of ammonia and nitrous oxide by amending a urea-based fertilizer with the urease inhibitor nBPT.

The final aim of this thesis is to highlight opportunities for improving the intensive agricultural system of the NCP and to offer suggestions for research that aims to deepen our understanding of N cycling in general

and the processes affecting nutrient cycling in China in special.

1.7 Structure of this thesis

Apart from the General Introduction and Discussion, this thesis includes 5 chapters that attend to the aims and objectives stated above. These chapters comprise three original research manuscript that have been published in international high-standard referenced and peer-reviewed journals [I, II, III], as well as one original research paper that was prepared for submission [V]. Further, one poster contribution has been included as an extended abstract [IV]:

[I] Reprinted from *Field Crops Research*, 174, Hartmann, T.E., Yue S.C., Schulz, R., He X.K., Chen X.P., Zhang F.S., Müller, T.: Yield and N use efficiency as affected by different fertilizer management strategies in a farmer's field of the North China Plain, 30 – 39, 2015, with permission from Elsevier.

[II] Reprinted from *Field Crops Research*, 160, Hartmann, T.E., Yue S.C., Schulz, R., Chen X.P., Zhang F.S., Müller, T.: Nitrogen dynamics, apparent mineralization and balance calculations in a maize - wheat double cropping system of the North China Plain, 22 – 30, 2014, with permission from Elsevier.

[III] Abstract reprinted from Nutrient Cycling in Agroecosystems, 98, Michalczyk, A., Kersebaum, K.C., Roelcke, M., Hartmann, T.E., Yue, S.C., Chen, X.P., Zhang F.S.: Model-based optimisation of nitrogen and water management for wheat-maize systems in the North China Plain, 203 – 222, 2014, with kind permission of Springer Science and Business Media.

[IV] Hartmann, T., A. Michalczyk, X.P. Chen, F.S. Zhang, T. Müller (2012): A Simplified Recommendation For Nitrogen Fertilization in a Wheat/Maize Double Cropping System in the North China Plain, Poster Contribution, Tagung der Deutschen Gesellschaft Für Pflanzenernährung, Bonn.

[V] Hartmann, T.E., Guzman-Bustamante, I., Ruser, R., Müller, T.: The turnover of urea in soil from the North China Plain as affected by the urease inhibitor NBPT and wheat straw.

The working progress of the research presented here is documented in the reports submitted to the Ministry of Education and Research (BMBF). This report will be submitted to the German National Library of Science and Technology (TIB):

(1) Innovatives Stickstoff-Management und innovative Technologien zur Verbesserung der landwirtschaftlichen Produktion und zum Schutz

der Umwelt in der Chinesischen Intensivlandwirtschaft , FKZ 0330800 ,
Schlussbericht (inhaltlicher Sachbericht) der Teilprojekte FKZ
0330800A-F

Yield and N use efficiency of a maize-wheat cropping system as affected by different fertilizer management strategies in a farmer's field of the North China Plain

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Field Crops Research (2015) 174: 30 - 39
DOI 10.1016/j.fcr.2015.01.006

Reprinted from Field Crops Research, 174, Hartmann, T.E., Yue S.C., Schulz, R., He X.K., Chen X.P., Zhang F.S., Müller, T.: Yield and N use efficiency as affected by different fertilizer management strategies in a farmer's field of the North China Plain, 30 – 39, 2015, with permission from Elsevier.



Yield and N use efficiency of a maize–wheat cropping system as affected by different fertilizer management strategies in a farmer’s field of the North China Plain



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article info

Article history:

Received 6 October 2014

Received in revised form 10 January 2015

Accepted 12 January 2015

Keywords:

North China Plain

Nitrogen use efficiency

Urea

Urea ammonium nitrate

Ammoniumsulphate nitrate

DMPP

abstract

This study aimed to identify whether nitrogen (N) use efficiency in a summer-maize/winter-wheat double-cropping system of the North China Plain (NCP) could be increased by adjusting N supply to crop N demand, and through the use of alternate N fertilizers and application strategies. In a static experiment conducted on a farmers’ field six reduced N treatments were compared to farmers’ practice (FP: 550 kg (N) ha⁻¹ a⁻¹) and a control treatment (CK).

With few exceptions of single treatments in single cropping-seasons, the optimized fertilization of N did not lead to a yield reduction of either summer-maize or winter-wheat. The grain yield of summer-maize ranged between 5.8 and 7.1 Mg ha⁻¹. The grain yield of wheat ranged between 4.4 and 6.2 Mg ha⁻¹.

For the first two vegetation periods of summer-maize, the recovery efficiency (RE_N; 0.09–0.30 kg kg⁻¹) and agronomic efficiency of N (AE_N) were mainly affected by the yield achieved in the control treatment (5.7 and 5.9 Mg ha⁻¹), which was not significantly reduced compared to most fertilized treatments. In the third vegetation period of summer-maize, an increase of RE_N of the reduced treatments (0.37–0.58 kg kg⁻¹) was determined compared to FP (0.21 kg kg⁻¹). In both vegetation periods of wheat RE_N of the reduced treatments (0.34–1.0 kg kg⁻¹) was significantly higher compared to FP (0.26 and 0.27 kg kg⁻¹). The highest cumulated AE_N, as well as cumulated grain yields were observed when ammonium sulphate nitrate + 3,4-dimethylpyrazolephosphate (ASN_{DMPP}) was applied according to crop N demand and residual soil mineral N. The highest RE_N was observed when urea ammonium nitrate was applied in a shallow, banded depot (UAN_{DEP}).

This research demonstrates that N application rates in a maize/wheat double cropping system may be significantly reduced compared to common farmers’ practice, without negatively affecting grain yield, thereby increasing N use efficiency.

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1. Introduction

The agricultural production of cereals in China, especially in the eastern production areas of the North China Plain (NCP), increased dramatically since 1960 as a result of the industrialized production of inexpensive synthetic nitrogen (N) fertilizers. Additionally, new high yield varieties also led to an increased production of cereals (Zhu and Chen, 2002).

Increasing the productivity of agricultural systems through the use of synthetic N is especially important for China, in order to feed the large population. The population has already increased to 1.3 billion people in 2010 and, depending on the variables used in

projections, may peak at about 1.4 billion by 2030 (Peng, 2011). The intensive cultivation of summer-maize/winter-wheat double-cropping systems in the NCP is reliant on the use of synthetic N fertilizers. The use of manure as an organic source of nutrients has become obsolete in rural areas, due to the separation of arable and live-stock farming operations (Schuchardt et al., 2011).

Even though the average yield of cereal crops is stagnating since the late 1980s, the input of synthetic N has continued to increase on a national scale. In average, total N inputs in China increased from 3081 kg km⁻² in 1985 to 5426 kg km⁻² in 2007 (Ti et al., 2012).

Productivity has therefore declined dramatically, as more synthetic N is expended for stagnating, or even decreasing, cereal production. This discrepancy has led to a strong decrease in N use efficiency (NUE) and to increased environmental pollution through agriculture as reactive N is lost through gaseous emission (N₂O, NO and N₂) and leaching (Subbarao et al., 2006; Li et al., 2007; Zhao et al., 2007; Ju et al., 2009). The environmental impact of reactive N in China has been evident for some time (Zhu and Chen, 2002), but the trend of increased N application has not been reversed so far. In addition to the high loss of reactive N to the environment and the problems that are caused thereby (Ju et al., 2007, 2011; Ti et al., 2012), atmospheric N deposition has doubled since the 1980s and is contributing to the over-supply of N to crops (Zhang et al., 2006; Ju et al., 2009).

As Galloway et al. (2008) made clear, it is necessary to reduce the loss of reactive N in agricultural systems in order to reverse this development; the measure of success being increased NUE (Cassman et al., 2002; Li et al., 2007). Three main strategies for increasing NUE have been suggested: The breeding of more N efficient crops (Raun and Johnson, 1999; Dawson et al., 2008); the development of stabilized fertilizers and innovative application techniques that reduce the risk of N losses; and the reduced application of N based on the evaluation of crop N demand and soil mineral N (N_{min}) at the time of fertilization (Lhada et al., 2005; Arregui and Quemada, 2006).

Although there were advances in breeding higher yielding varieties with more efficient uptake systems, short term steps for reducing the loss of N from agricultural systems are necessary to improve Chinese agriculture. The only feasible short term step in this direction is reducing the amount of N that is applied to crops.

The adjustment of N application rates, with the aim of reducing excess N, is based on two measures: (1) the calculation of the crop's N demand, based on the expected yield level of the crop, and on the N content of the harvested products and (2) the analysis of N_{min} at the time of fertilization, which allows the adjustment of N application rates to ensure that total N supply does not exceed the demand of the crop (Wehrmann and Scharpf, 1979).

In addition to reducing the application rate of N, it is possible to take measures that reduce the loss of N after application. Examples are stabilized N fertilizers, which contain nitrification inhibitors (NI) such as dicyandiamide (DCD) or 3,5-dimethylpyrazol phosphate (DMPP). Thereby, N remains in ammoniacal form through the inhibition of nitrification (Lhada et al., 2005).

The banded sub-surface application of ammonium-based fertilizers, such as urea ammonium nitrate (UAN), ammonium sulphate nitrate (ASN) or urea, also aims to delay nitrification. Here, the concentrated application of ammonium-based N sources should inhibit nitrifying bacteria through toxic concentrations of ammonium within the depot, thereby retaining N in the soil and reducing both volatilization as well as leaching of applied N (Zerulla et al., 2001).

The aim of this research was to apply strategies for the reduction of N input, as mentioned above, in a previously over-fertilized farmers' field, managed as an intensive summer-maize/winter-wheat double cropping system, with a special emphasis on the application techniques and N fertilizers.

The main hypotheses for this research were, that (1) the reduction of N application according to crop demand and soil mineral N status will (i) have no negative effect on the yield in the double cropping system, (ii) reduce the excessive application of fertilizer N surpluses and (iii) increase N use efficiency, namely the recovery efficiency (RE_N) and agronomic efficiency of N (AE_N).

Further, (2) N forms other than the predominantly used urea will be more suitable for conditions in the NCP (i) in terms of grain yield and N use efficiency, and (ii) ammonium-based fertilizers that are stabilized either through the NI DMPP or by placed sub-surface application will achieve higher yields and N efficiency compared to conventional methods of N application.

The results of this study should in further steps be used to identify strategies for the reduction of N application in the NCP and to develop fertilizer recommendations for small-scale farmers of the region.

2. Materials and methods

2.1. Study site

As previously described (Hartmann et al., 2014), the experiment was carried out in a farmer's field adjacent to the research station of the China Agricultural University (CAU) in Quzhou County, Hebei Province, PRC (115°E, 36°N, 40 masl).

The soil of the experimental site is classified as a Cambisol with a silt loam texture according to IUSS Working Group WRB (2007). The soil shows a total C concentration of 1.8%, a total N concentration of 0.1% and 110 mg (P) kg (soil)⁻¹. The pH of the soil (CaCl₂) is 7.5. The weather pattern is described as a monsoon influenced steppe climate, with a mean temperature and precipitation at the study site of 13.6 °C and 490 mm (1980 to 2009), respectively. About 60% of precipitation occur between July and September.

The farmer's field chosen for this study was previously managed as a summer-maize/winter-wheat double-cropping system common in the area, with an annual N fertilization rate of about 550 kg (N) ha⁻¹ a⁻¹. By request, the farmer did not carry out spring fertilization of wheat (150 kg N ha⁻¹) in order to reduce soil mineral N levels in the field before beginning experiments. The measured N_{min} content of the soil (0–90 cm) after the farmer's wheat harvest was 30 kg N ha⁻¹.

2.2. Experimental design

8 N fertilizer treatments, with four replications were included in the experiment. The replications were fully randomized in a 8 × 4 Latin rectangle. Each plot had a size of 68 m². The total size of the field was 72 m × 34 m. Plots were separated by 15 cm earthen dams to allow flood irrigation of each plot. The experimental blocks were separated by 1 m walkways.

After the first experimental year, it was decided to perform this experiment as a 2.5 year static field trial with 3 seasons of summer-maize and 2 seasons of winter-wheat. The high fertilization level before the beginning of the experiment led to an extreme subsequent delivery of mineral N from the soil pool (Hartmann et al., 2014), making it necessary to remain in the same field in order to answer the hypotheses of this experiment.

2.3. Fertilizer treatments

To compare the effect of reduced N application and of different N fertilizer strategies, 8 treatments were included in the experiment. These were 2 control treatments (Control (CK), farmers practice (FP)), and 6 optimized treatments, fertilized according to crop N demand and soil mineral N (N_{min}). In 4 of these optimized treatments (UREA_{SPLIT}, UREA, ASN_{DMPP}, UAN) N was broadcast by hand

Table 1
Experimental Treatments, N application rates, timing and application technique.

Treatment	Maize			Wheat			
	Appl. No.	N rate kg (N) ha ⁻¹	Leaf stage	Appl. no.	N rate kg (N) ha ⁻¹	Growth stage	Method
CK	–	–	–	–	–	–	–
FP _{CK}	–	–	–	–	–	–	–
FP	1	250	4–6	2	2 150	Sowing + regreening	Broadcast
UREA _{SPLIT}	2	200–N _{min}	4 6 (70%) + 10 (30%)	2	200–N _{min}	Regreening (70%) + shooting (30%)	Broadcast
UREA	1	200–N _{min}	4–6	1	200–N _{min}	Regreening	Broadcast
ASN _{DMPP}	1	200–N _{min}	4–6	1	200–N _{min}	Regreening	Broadcast
UAN	1	200–N _{min}	4–6	1	200–N _{min}	Regreening	Broadcast
UAN _{DEP}	1	200–N _{min}	4–6	1	200–N _{min}	Regreening	Sub-surface banded
UREA _{DEP}	1	200–N _{min}	4–6	1	200–N _{min}	Regreening	Sub-surface banded

CK = control, FP_{CK} = control (maize 2011), FP = farmer's practice, UREA = reduced (urea), ASN_{DMPP} = ammoniumsulphate nitrate + DMPP, UAN = urea ammoniumnitrate solution, SPLIT = 2 Applications, DEP = sub-surface-banded.

(UAN: hand-operated knapsack sprayer). For the remaining 2 treatments (UREA_{DEP}, UAN_{DEP}) N was applied as banded sub-surface depot between plant rows at a depth of 5 to 10 cm. Solid fertilizer (UREA_{DEP}) was applied using a modified tractor-mounted seeding device. Liquid fertilizer (UAN_{DEP}) was applied into prepared bands using a hand-operated backpack sprayer (Table 1).

Four treatments (FP, UREA_{SPLIT}, UREA and UREA_{DEP}) were fertilized with urea N source, 2 treatments (UAN, UAN_{DEP}) were fertilized with Urea Ammoniumnitrate solution. The remaining treatment (ASN_{DMPP}) was fertilized with ammoniumsulphate nitrate + 3,4-dimethyl pyrazolephosphate (Entec 26©) (Table 1).

The application rate of N for the reduced treatments was calculated from yield expectations for wheat and maize in the region and from N_{min} at a depth of 0–90 cm. For both maize and wheat, the N demand over the vegetation period was calculated as 200 kg (N) ha⁻¹ at yield expectations of 8–10 Mg (grain) ha⁻¹ for maize and 8 Mg (grain) ha⁻¹ for wheat, respectively (Table 1).

N_{min} sampling for the determination of N application rates was carried out two days before fertilization. Soil samples from each treatment were immediately processed and analyzed for soil nitrate-N using a nitrate quick test (see soil analysis) to determine N application rates of each treatment. Due to the heterogeneity of N_{min} concentrations within the field, N rates were adjusted for each treatment separately.

As previously mentioned, the previous high fertilization levels of the farmer led to a strong resupply of N in the field (Hartmann et al., 2014). In order to distinguish whether the observed effects should be attributed to N mineralization or N deposition, the FP plot was separated into two smaller plots of 34 m² for the final vegetation period of maize. One of these plots (FP) was top-dressed with 250 kg (N) ha⁻¹, the remaining plot (FP_{CK}) did not receive top-dressing at 4–6 leaf stage (Table 1).

2.4. Field management

Field management, apart from the top-dressing of N, followed current farmers' practice typical for the region. Maize (cultivar "Zhengdan") was sown at a density of ca. 75,000 seeds ha⁻¹ in the middle of June, with a side-dress of 30 kg (N) ha⁻¹ applied as 15–15–15 NPK compound fertilizer. For technical reasons, all treatments, including CK, were fertilized accordingly. Depending on rainfall events, the field was flood-irrigated after sowing. After the manual harvest of the maize-cobs (October), plant residues (maize-stalks) were trimmed using a threshing machine for easier incorporation, before base-fertilizer (120 kg (P₂O₅) ha⁻¹, 90 kg (K₂O) ha⁻¹) for the subsequent winter-wheat crop was applied. The field was then plowed to a depth of 20 cm and rotary-cultivated to prepare the seed bed. Winter-wheat (cultivar "Liangxing99") was sown at a row spacing of 15 cm and subsequently flood irrigated. After the

machine harvest of wheat in June plant residues remained on the soil surface.

2.5. Soil analysis

Soil mineral nitrogen (N_{min}) was determined for each layer separately at 0–30, 30–60 and 60–90 cm depth. Soil samples for the vegetation period of maize were taken immediately before sowing in May and 2 days prior to fertilization events in June (4–6 leaf stage) and early July (10 leaf stage). Sampling for the vegetation period of wheat was carried out immediately before sowing and 2 days prior to fertilization events in March (regreening) and April (shooting). The sampling dates were not fixed, but adjusted to the growth stages of the cropping system. 5 samples were taken per plot, homogenized and passed through a 0.5 cm sieve. Water content of the samples was determined gravimetrically, and soil samples were extracted with 0.01 M CaCl₂ at a soil:solution ratio of 1:8. For the calculation of N_{min} before fertilization, nitrate was determined through reflectometry using nitrate test-strips (Merck Millipor, RQeasy quick-test). Previous Research has shown that there is a very close correlation of results between nitrate test-strips and laboratory analysis (Schmidhalter, 2005; Cui et al., 2005). Further, samples were analyzed for NO₃-N and NH₄-N through micro-flow auto-analysis (SEAL QuAAtro).

2.6. Yield determination

Grain yield of maize was determined through manual harvest of a 10.8 m² sample in the center of the individual plots. In the final vegetation period of maize, the sampling area of the divided FP plots (FP and FP_{CK}) was 5.4 m². Sub-samples were taken for the determination of grain water-content and grain N and C. Plants from the sample area were used for biomass estimation, plant water content and plant N and C.

The yield of wheat was determined using 3 samples of each 1 m². Grain and plant material were separated, and sub-samples of the grain and plant material were further processed for the determination of water-content and grain and plant N and C.

2.7. Plant analysis

Grain and plant material were prepared for analysis through oven-drying and homogenization using a rotating-disc mill. N and C content were determined through high-temperature combustion and subsequent gas analysis (Elementar Analysensysteme GmbH, Vario MAX CN).

2.8. Calculation of the components of N use efficiency

The components of N use efficiency, namely the Recovery Efficiency (RE_N) and Agronomic Efficiency of fertilized N (AE_N), were calculated as described by [Lhada et al. \(2005\)](#).

The calculations for the single components are carried out as follows:

$$RE_N = \frac{(U_T - U_{CK})}{N_F} = \frac{\Delta U}{N_F} \text{ (kg kg}^{-1}\text{)} \quad (1)$$

where U_T and U_{CK} are N in the grain of the fertilized treatment and control treatment at harvest, respectively, and N_F is the amount of N applied as fertilizer.

$$AE_N = \frac{(Y_T - Y_{CK})}{N_F} = \frac{\Delta Y}{N_F} \text{ (kg kg}^{-1}\text{)} \quad (2)$$

where Y_T and Y_{CK} are the grain yield of the fertilized treatment and control treatment at harvest, respectively, and N_F is the amount of N applied as fertilizer.

Due to the static character of this field trial, the interpretation of the calculated indicators must consider the increasing N-depletion of the CK treatment throughout the experimental seasons. RE_N and AE_N were therefore calculated for the cumulated values of fertilized N, recovered N and cumulated grain yield (grain equivalent units: GEU).

2.9. Statistical analysis

The experimental results were analyzed using the R programming environment for statistical computing ([R Development Core Team, 2011](#)). Experimental data was subjected to Fisher's test for least significant difference (LSD), at a confidence interval of $\alpha = 0.05$.

Correlations between N-supply ($N_{min} + N_F$) and the yield of both maize and wheat were fitted through polynomial regression. Correlations between F_N and components of N use efficiency were fitted through exponential regression.

3. Results

3.1. Yield

Due to the restrictions of the double cropping system and according to current farmers' practice in the area, summer-maize was harvested before senescence had completed and the kernel milk-line had disappeared. The grain water content of summer-maize was therefore ca. 40% in all three seasons of the experiment. The average grain yield of maize in treatment CK was 5.7 and 5.9 Mg (dw) ha⁻¹ in 2009 and 2010, respectively. In 2011 the yield was significantly lower (3.4 Mg (dw) ha⁻¹) compared to the first two vegetation periods of maize ([Table 2](#)). In 2011, the grain yield of the unfertilized FP_{CK} (6.6 Mg ha⁻¹) differed neither from the fertilized FP treatment (6.3 Mg ha⁻¹) nor from any of the reduced N treatments ([Table 2](#)). The high yields of the CK treatment in the first two vegetation periods of maize were therefore attributed to the high re-supply of soil N following previous farmers' practice.

In 2009, treatments ASN_{DMPP} (6.9 Mg ha⁻¹) and UAN (6.9 Mg ha⁻¹) achieved significantly higher yields compared to CK (5.7 Mg ha⁻¹). There was no significant difference in yield between the optimized treatments and FP.

In 2010, the highest yield was observed in treatment UREA (7.2 Mg ha⁻¹), which was significantly higher compared to both CK (5.9 Mg ha⁻¹) and FP (6.0 Mg ha⁻¹), but not compared to the remaining experimental treatments.

Of the fertilized treatments in 2011, the lowest yield was observed for UREA (5.8 Mg ha⁻¹), which was significantly lower compared to treatment UAN (7.1 Mg ha⁻¹), but not to the remaining fertilized treatments.

For the first two observation periods of maize, no correlation between N supply and grain yield of maize could be determined (data not shown). In 2011, a correlation between N-supply ($N_{min} + N_F$) and grain yield of maize was determined through polynomial regression at an adjusted R² of 0.94 ($p > 0.05$) ([Fig. 1A](#)).

Table 2

Grain yield (DW), total aboveground biomass and N contents of summer-maize at harvest over three experimental seasons. SE indicates standard error of the mean. Letters indicate significant differences between treatments within one year ($\alpha = 0.05$, Fisher's LSD).

Crop	Year	Treatment	Grain yield (Mg ha ⁻¹)	SE	Total biomass (Mg ha ⁻¹)	SE	N in grain (kg (N) ha ⁻¹)	SE	N in biomass (kg (N) ha ⁻¹)	SE
Maize	2009	CK	5.7	0.31 b	19.8	1.3 b	72	3.6 b	198	18.2 b
		FP	6.4	0.24 ab	21.2	0.5 ab	90	3.8 a	234	16.9 ab
		UREA _{SPLIT}	6.1	0.65 ab	21.4	1.6 ab	93	9.4 a	243	24.3 ab
		UREA	6.6	0.16 ab	21.5	0.6 ab	92	5.6 a	242	6.3 ab
		ASN _{DMPP}	6.9	0.33 a	23.2	1.8 a	96	3.4 a	266	19.6 a
		UAN	6.9	0.23 a	21.8	1.2 ab	95	2.8 a	240	10.6 ab
		UAN _{DEP}	6.3	0.20 ab	20.0	0.9 ab	89	2.9 a	222	7.1 ab
		UREA _{DEP}	6.6	0.71 ab	21.1	0.8 ab	88	8.8 a	229	8.8 ab
		CK	5.9	0.23 b	12.3	0.5 b	67	5.1 b	111	7.5 c
	2010	FP	6.0	0.06 b	14.7	0.6 a	88	3.0 a	189	7.0 a
		UREA	6.8	0.45 ab	13.6	0.5 ab	90	5.4 a	151	6.0 b
		UREA _{SPLIT}	7.2	0.29 a	13.2	0.4 ab	97	4.4 a	152	1.0 b
		ASN _{DMPP}	6.7	0.39 ab	13.0	0.6 ab	89	4.9 a	150	7.3 b
		UAN	6.6	0.66 ab	13.5	1.0 ab	87	9.0 a	151	9.2 b
		UAN _{DEP}	6.6	0.23 ab	12.6	1.0 b	87	5.0 a	144	11.2 b
		UREA _{DEP}	6.3	0.28 ab	13.0	0.6 b	84	4.4 a	146	8.5 b
		CK	3.4	0.22 c	9.0	1.2 b	37	1.3 c	83	10.4 c
		2011	FP _{CK}	6.6	0.36 ab	11.8	0.7 ab	84	4.5 ab	137
FP	6.3		0.54 ab	12.6	1.2 a	78	5.7 b	146	14.2 ab	
UREA _{SPLIT}	6.3		0.22 ab	12.8	1.0 a	81	3.8 b	145	11.8 ab	
UREA	5.8		0.45 b	11.3	1.0 ab	73	6.1 b	126	9.0 b	
ASN _{DMPP}	6.2		0.33 ab	12.6	1.0 a	79	5.2 b	150	17.4 ab	
UAN	7.1		0.33 a	13.3	1.2 a	96	4.8 a	160	6.8 ab	
UAN _{DEP}	6.5		0.19 ab	13.1	0.8 a	87	4.2 ab	160	11.9 ab	
UREA _{DEP}	6.4		0.19 ab	14.1	1.2 a	86	5.1 ab	169	15.5 a	

CK = control, FP_{CK} = control (maize 2011), FP = farmer's practice, UREA = reduced (urea), ASN_{DMPP} = ammoniumsulphate nitrate + DMPP, UAN = urea ammoniumnitrate solution, SPLIT = 2 Applications, DEP = sub-surface-banded.

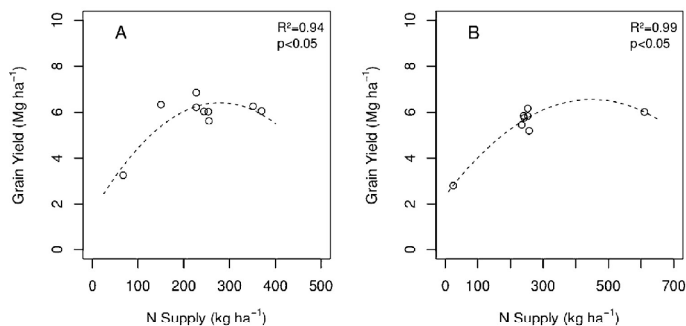


Fig. 1. N supply ($N_f + N_{\min}$ kg ha^{-1}) and the mean grain yields of maize (A) and wheat (B) in the final experimental seasons of 2011, as observed for the experimental treatments of the experiment.

The total aboveground biomass of maize as an average of all treatments decreased from ca. 21 Mg ha^{-1} in 2009 to ca. 12.5 Mg ha^{-1} in 2011. In 2009, total aboveground biomass of treatment CK (19.8 Mg ha^{-1}) did not differ significantly from the fertilized treatments except from treatment ASN_{DMPP} (23.2 Mg ha^{-1}), which in turn was not significantly higher compared to the remaining fertilized treatments. In 2010, total aboveground biomass of FP (14.7 Mg ha^{-1}) was significantly higher compared to CK, UREA_{DEP} and UAN_{DEP} (12.3 , 12.6 , 13.0 Mg ha^{-1}), but not compared to the remaining fertilized treatments (Table 2). In 2011, aboveground biomass of treatment CK (9.0 Mg ha^{-1}) was significantly lower compared to all treatments except treatments FP and UREA (11.8 and 11.3 Mg ha^{-1}).

The omission of N application in treatment CK led to an immediate grain yield depression of wheat in 2010 (1.8 Mg ha^{-1}) and 2011 (2.8 Mg ha^{-1}), with significantly lower yields compared to all fertilized treatments in both years (Table 3).

In both 2010 and 2011, the highest yield was achieved in treatment ASN_{DMPP} (5.6 and 6.2 Mg ha^{-1}). The lowest observed yield of the fertilized treatments were UREA in 2010 (4.4 Mg ha^{-1}) and UAN_{DEP} in 2011 (5.2 Mg ha^{-1}). The yield of treatment FP did not differ significantly to any of the reduced N treatments in 2010 (4.7 Mg ha^{-1}) and only to treatment UAN_{DEP} in 2011 (6.0 Mg ha^{-1}).

Total aboveground biomass production of wheat was significantly lower in treatment CK compared to all fertilized treatments in both 2010 (5.8 Mg ha^{-1}) and 2011 (4.5 Mg ha^{-1}). There were no significant differences between the fertilized treatments with the exception of treatment UREA_{DEP} (13.2 Mg ha^{-1}) and UAN (11.1 Mg ha^{-1}) in 2010, and between both ASN_{DMPP} (11.3 Mg ha^{-1}) and FP (11.5 Mg ha^{-1}) compared to treatment UAN_{DEP} (9.4 Mg ha^{-1}) in 2011.

A strong correlation between the grain yield of wheat and N supply ($N_{\min} + N_f$) was determined both in 2010 (data not shown) and 2011 through polynomial regression at an adjusted R^2 of 0.98, $p > 0.05$ (Fig. 1B).

The comparison of total grain yield achieved over 5 vegetation periods resulted in a significantly higher yield of the ASN_{DMPP} treatment (34.9 Mg (grain equivalent units— GEU) ha^{-1}) and UAN treatment compared to treatments $\text{UREA}_{\text{SPLIT}}$ ($31.7 \text{ Mg (GEU)} \text{ ha}^{-1}$), UREA ($32.2 \text{ Mg (GEU)} \text{ ha}^{-1}$) and UAN_{DEP} ($32.1 \text{ Mg (GEU)} \text{ ha}^{-1}$), while no significant difference could be determined for either treatment FP ($32.7 \text{ Mg (GEU)} \text{ ha}^{-1}$) or UREA_{DEP} ($33.5 \text{ Mg (GEU)} \text{ ha}^{-1}$) compared to the other fertilized treatments. Treatment CK ($21.6 \text{ Mg (GEU)} \text{ ha}^{-1}$) achieved a significantly lower yield compared to all fertilized treatments (Fig. 2A).

3.2. Nitrogen content

N determined in the grain of maize was significantly lower in treatment CK compared to all fertilized treatments in all three periods of observation (72 , 67 , $37 \text{ kg (N)} \text{ ha}^{-1}$). In 2009 and 2010, there was no significant difference in grain N between the fertilized treatments. In 2011, the highest grain N was determined in treatment UAN ($96 \text{ kg (N)} \text{ ha}^{-1}$) which was significantly higher compared to treatments FP_{CK}, $\text{UREA}_{\text{SPLIT}}$, UREA and ASN_{DMPP} (84 , 81 , 73 , $79 \text{ kg (N)} \text{ ha}^{-1}$) (Table 2).

In 2009, total N in aboveground biomass was lowest in treatment CK ($198 \text{ kg (N)} \text{ ha}^{-1}$) and highest in treatment ASN_{DMPP} ($266 \text{ kg (N)} \text{ ha}^{-1}$), which significantly differed from each other. The remaining treatments showed no significant differences. In 2010, N in aboveground biomass of treatment CK ($111 \text{ kg (N)} \text{ ha}^{-1}$) was significantly lower compared to all fertilized treatments. The reduced N treatments were all significantly lower compared to treatment FP ($189 \text{ kg (N)} \text{ ha}^{-1}$). In 2011, total N in aboveground biomass was significantly lower in treatment CK ($83 \text{ kg (N)} \text{ ha}^{-1}$) as compared to all other treatments. The highest aboveground N amount was determined in treatment UREA_{DEP} ($169 \text{ kg (N)} \text{ ha}^{-1}$), which significantly differed from treatment UREA ($126 \text{ kg (N)} \text{ ha}^{-1}$), but not to the remaining fertilized treatments (Table 2).

In accordance with the results for grain yield, the N uptake in the grain of winter-wheat of the CK treatment was significantly lower compared to all fertilized treatments. Similar to maize, the N amount in the grain of fertilized treatments did not differ, with few exceptions (Table 3).

The highest aboveground N uptake was observed in the FP treatment, which accumulated $181 \text{ kg (N)} \text{ ha}^{-1}$ in aboveground biomass in 2010 and $175 \text{ kg (N)} \text{ ha}^{-1}$ in 2011 (Table 3).

3.3. Fertilizer application

Following the determination of the N_{\min} status of the soil, the application rates of fertilized N were highly reduced compared to the application rates of the FP treatment. In spite of fluctuations between treatments in the individual years of the experiment (Table 4), the cumulated rates of N application over 5 vegetation periods (2.5 years) are in a similar range. While the total application of N for the FP treatment amounted to $1350 \text{ kg (N)} \text{ ha}^{-1}$ over the duration of the experiment, the total application of N in the reduced treatments ranged between 705 (UREA_{DEP}) and $750 \text{ kg (N)} \text{ ha}^{-1}$ (UAN). Compared to FP, total N application over 5 vegetation periods was reduced by 44 to 48%.

Table 3

Grain yield (DW), total aboveground biomass and N contents of winter-wheat at harvest over two experimental seasons. SE indicates standard error of the mean. Letters indicate significant differences between treatments ($\alpha=0.05$, Fisher's LSD).

Crop	Year	Treatment	Grain yield (Mg (dw)ha ⁻¹ SE)	Total biomass (Mg (dw) ha ⁻¹ SE)	N in grain (kg ha ⁻¹ SE)	N in biomass (kg ha ⁻¹ SE)
Wheat	2010	CK	1.8 0.25 c	5.8 0.6 c	36 4.8 c	54 5.9 e
		FP	4.7 0.10 ab	12.9 0.2 ab	113 2.6 ab	181 3.3 a
		UREA _{SPLIT}	4.9 0.74 ab	12.2 0.3 ab	92 16.3 ab	144 12.2 bcd
		UREA	4.4 0.09 b	11.3 0.2 ab	86 14.9 b	126 23.3 cd
		ASN _{DMPP}	5.6 0.58 a	12.8 0.2 ab	125 13.4 a	172 12.0 abc
		UAN	4.7 0.16 ab	11.1 1.0 b	106 3.5 ab	145 7.6 d
		UAN _{DEP}	4.6 0.50 b	11.8 0.3 ab	101 2.1 b	149 1.6 cd
	2011	UREA _{DEP}	5.2 0.16 ab	13.2 1.3 a	122 10.7 a	179 13.1 ab
		CK	2.8 0.04 d	4.5 0.2 c	63 5.1 c	69 6.1 c
		FP	6.0 0.09 ab	11.5 0.3 a	144 3.0 a	175 4.1 a
		UREA _{SPLIT}	5.4 0.21 bc	10.6 0.5 ab	126 4.3 b	151 5.1 b
		UREA	5.7 0.26 abc	10.2 0.8 ab	131 5.9 ab	157 8.5 ab
		ASN _{DMPP}	6.2 0.34 a	11.3 0.8 a	146 11.8 a	165 14.9 ab
		UAN	5.8 0.24 ab	10.5 0.8 ab	133 5.9 ab	157 7.3 ab
UAN _{DEP}	5.2 0.18 c	9.4 0.7 b	125 3.6 b	147 5.4 b		
UREA _{DEP}	5.8 0.12 ab	10.8 0.2 ab	134 4.0 ab	157 3.6 ab		

CK = control, FP_{CK} = control (maize 2011), FP = farmer's practice, UREA = reduced (urea), ASN_{DMPP} = ammoniumsulphate nitrate + DMPP, UAN = urea ammoniumnitrate solution, SPLIT = 2 Applications, DEP = sub-surface-banded.

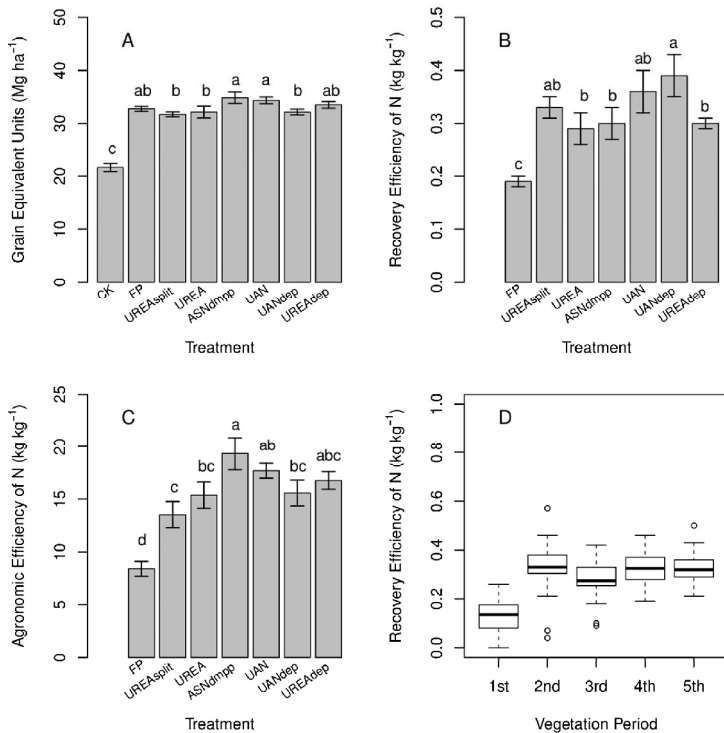


Fig. 2. Cumulated grain yield of 5 vegetation periods (kg (grain equivalent units) ha⁻¹ (A), cumulated recovery efficiency (RE_N) (B), agronomic efficiency of N (AE_N) (C) and cumulated development of RE_N of the reduced N treatments over 5 vegetation periods (D). Error bars indicate the standard error of the mean, letters above error bars indicate differences between treatments ($\alpha=0.05$, Fisher's LSD).

Table 4
Fertilized N and indicators of N use efficiency calculated for the fertilized experimental treatments of summer-maize and winter-wheat. Agronomic efficiency of N was only calculated when significant differences in basic yield data between fertilized and control (CK) treatments were significant. SE indicates standard error of the mean. Letters indicate significant differences between treatments ($\alpha=0.05$, Fisher's LSD).

Treatment	Summer maize 2009			Winter wheat 2009–2010		
	N _F (kg ha ⁻¹)	RE _N (kg kg ⁻¹)	AE _N (kg kg ⁻¹)	N _F (kg kg ⁻¹)	RE _N (kg kg ⁻¹)	AE _N (kg kg ⁻¹)
FP	250	0.09	0.02	300	0.26	0.02 c
UREA _{SPLIT}	190	0.08	0.06	115	0.50	0.17 c
UREA	190	0.13	0.04	90	0.55	0.15 c
ASN _{DMPP}	190	0.15	0.02	100	0.89	0.15 ab
UAN	190	0.15	0.02	120	0.58	0.01 bc
UAN _{DEP}	190	0.11	0.03	120	0.53	0.04 c
UREA _{DEP}	190	0.11	0.05	80	1.0	0.12 a
	Summer maize 2010			Winter wheat 2010–2011		
	N _F (kg ha ⁻¹)	RE _N (kg kg ⁻¹)	AE _N (kg kg ⁻¹)	N _F (kg kg ⁻¹)	RE _N (kg kg ⁻¹)	AE _N (kg kg ⁻¹)
FP	250	0.10	0.03 c	300	0.27	0.02 c
UREA _{SPLIT}	155	0.19	0.05 bc	185	0.34	0.01 bc
UREA	135	0.30	0.03 ab	170	0.41	0.02 b
ASN _{DMPP}	135	0.21	0.04 abc	160	0.51	0.06 a
UAN	135	0.22	0.09 abc	175	0.40	0.04 b
UAN _{DEP}	90	0.34	0.06 a	175	0.36	0.00 bc
UREA _{DEP}	160	0.13	0.04 c	180	0.40	0.03 b
	Summer maize 2011					
	N _F (kg ha ⁻¹)	RE _N (kg kg ⁻¹)	AE _N (kg kg ⁻¹)			
FP	250	0.21	0.02 d	14.3	2.2	c
UREA _{SPLIT}	100	0.47	0.04 abc	28.6	1.1	ab
UREA	130	0.37	0.06 c	24.2	4.4	b
ASN _{DMPP}	130	0.42	0.04 bc	28.1	2.9	b
UAN	130	0.58	0.05 a	37.1	3.7	a
UAN _{DEP}	130	0.49	0.04 ab	30.9	3.0	ab
UREA _{DEP}	130	0.43	0.03 bc	30.1	2.2	ab

N_F: fertilized nitrogen (kg N ha⁻¹); RE_N: recovery efficiency of N (kg(N Grain)/kg(N fertilized)⁻¹); AE_N: agronomic efficiency of N (kg(Grain)/kg(N fertilized)⁻¹).

This reduction of N application rates led to a reduced N supply (N_{min} + N_F) in the final vegetation periods of both maize and wheat. For maize, the total N supply for the optimized treatments was approximately 230 kg (N) ha⁻¹ compared to approximately 380 kg (N) ha⁻¹ for FP. For wheat, the total N supply of the optimized treatments was about 250 kg (N) ha⁻¹ compared to almost 650 kg (N) ha⁻¹ for FP (Fig. 1).

3.4. Components of N use efficiency

Due to the high variability of the data, no significant differences in RE_N were determined for the first season of maize in 2009. RE_N of maize ranged between 0.09 kg kg⁻¹ (FP) and 0.15 kg kg⁻¹ (ASN_{DMPP}). In 2010, the lowest RE_N was calculated for treatment FP (0.10 kg kg⁻¹). The highest RE_N was determined for treatment UAN_{DEP} (0.34 kg kg⁻¹), which had received merely 90 kg (N) ha⁻¹ (Table 4).

In 2011, RE_N increased following the yield depression in treatment CK. All optimized treatments showed a significantly higher RE_N compared to FP (0.21 kg kg⁻¹). The highest RE_N was determined for UAN (0.58 kg kg⁻¹) and UAN_{DEP} (0.49 kg kg⁻¹) (Table 4). The data of maize showed a correlation between N_F and RE_N at an adjusted R² of 0.63, p < 0.05 (Fig. 3A).

As no significant differences in grain yield between most fertilized treatments and CK were determined in both 2009 and 2010, the agronomic efficiency of N (AE_N) is indeterminable for these treatments in the first two vegetation periods of maize. The exceptions were ASN_{DMPP} and UAN in 2009, which both had an AE_N of 8.2 kg kg⁻¹, and treatment UREA in 2010, which had an AE_N of 12.0 kg kg⁻¹. In 2011, following the yield depression of treatment CK, AE_N of treatment FP was significantly lowest at 14.3 kg kg⁻¹. No differences between most reduced treatments were determined. The highest AE_N was achieved in treatment UAN (37.1 kg kg⁻¹),

which significantly differed from treatments UREA (24.2 kg kg⁻¹) and ASN_{DMPP} (28.1 kg kg⁻¹) (Table 4).

As the wheat yield of the CK treatment was significantly lower compared to the fertilized treatments in both 2010 and 2011, components of N use efficiency were calculated for all fertilized treatments (Table 4). RE_N of wheat decreased with increasing application rates of N, showing a correlation between the RE_N of wheat and N_F at an adjusted R² of 0.92, p < 0.05 (Fig. 3B). RE_N of the FP treatment, at 0.26 and 0.27 kg kg⁻¹ in 2010 and 2011, respectively, was significantly lower compared to all reduced treatments except UREA_{SPLIT} (0.34 kg kg⁻¹) and UAN_{DEP} (0.36 kg kg⁻¹) in 2011 (Table 4). Overall the RE_N of reduced treatments decreased from above 0.5 kg kg⁻¹ in 2010 to less than 0.51 kg kg⁻¹ in 2011, as N application rates increased following lower N_{min} levels before fertilization. AE_N of wheat decreased with increasing application rates of N in a similar manner (Table 4).

The highest cumulated RE_N (5 vegetation periods; 2.5 years) was achieved by treatment UAN_{DEP} (0.39 kg kg⁻¹) which differed significantly from treatments UREA, ASN_{DMPP} and UREA_{DEP} (0.29, 0.30 and 0.30 kg kg⁻¹), but not from treatments UREA_{SPLIT} and UAN (0.33 and 0.36 kg kg⁻¹). RE_N of treatment FP (0.19 kg kg⁻¹) was significantly lower compared to all reduced N treatments of the experiment (Fig. 2B).

The highest cumulated AE_N was achieved by treatment ASN_{DMPP} (19.32 kg kg⁻¹), which differed significantly from treatments UREA_{SPLIT}, UREA, and UAN_{DEP} (13.5, 15.4 and 15.6 kg kg⁻¹), but not from treatments UAN and UREA_{DEP} (17.7 and 16.75 kg kg⁻¹). The significantly lowest AE_N was achieved by treatment FP (8.4 kg kg⁻¹) (Fig. 2C).

The development of RE_N over 5 vegetation periods (2.5 years) shows that RE_N of summer-maize increased over time, as application rates of N were reduced and the N_{min} concentration of the CK treatment depleted (Fig. 2D).

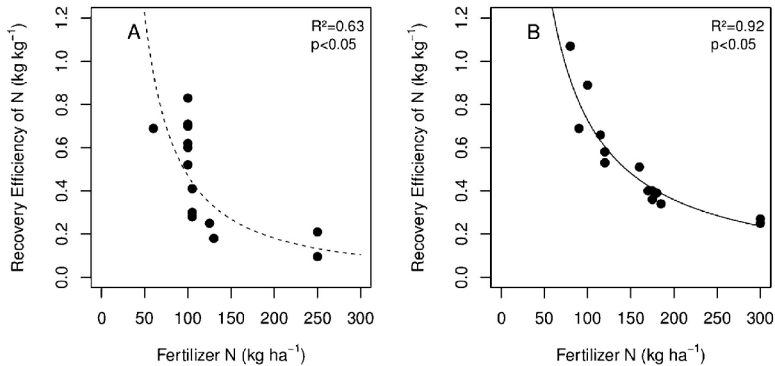


Fig. 3. Correlation between fertilizer N (kg ha⁻¹) and the mean recovery efficiency (RE_N) for the final two seasons of maize (A), and the mean RE_N for the two seasons of wheat (B) as observed in the experiment (RE_N: kg(N recovered)/kg(N_e)⁻¹).

4. Discussion

4.1. Applicability of the N_{min} based system

The results described here show that the calculation of N application rates according to crop N demand and the N_{min} status of the soil is helpful in reducing N application rates in a previously over-fertilized farmer's field, while maintaining the yield level of a summer-maize/winter-wheat double cropping system. These results are in accordance with previous research carried out in the same geographical region (Chen, 2003; Cui et al., 2006; Meng et al., 2012), where similar approaches for the determination of N application rates were used. Despite fluctuations in yield during individual cropping seasons, the total yield, as well as the total amount of N removed in harvested grain of the reduced N treatments was maintained compared to FP, while N application rates were reduced by approximately 45% over a period of 5 subsequent crops. Therefore, the excess of N in relation to crop demand was considerably reduced. In general, these results are in accordance with the research of Chen (2003) and Cui et al. (2006), who stated that the application of N according to FP in no way increases productivity, but increases the risk of N loss to the environment.

Farmers in the area frequently state that the high application rates of N are necessary as an "insurance" for soil-fertility (Cui et al., 2008a; Ju et al., 2009). As the results of this experiment confirm, there is no basis for this approach, as the N supply of soils and the addition of fertilizer N exceeds plant requirements by up to 500 kg N ha⁻¹ (Fig. 1). On the contrary, higher yields may be achievable in the long-term if application rates of N are reduced.

The N_{min} based approach to N application increased N use efficiency compared to FP, thereby confirming that the best approach toward increased fertilizer efficiency lies in the reduction of N application rates (Lhada et al., 2005; Subbarao et al., 2006). As the re-supply of N in the CK treatment led to comparably low values of RE_N as well as AE_N, especially in the first two vegetation periods of maize, it is more appropriate to observe over-all N use efficiency of the double-cropping system against a continuously decreasing control (Fig. 2D). These results indicate that it is possible over time to increase N use efficiency of cereal crops in the NCP above the world-average of maize (RE_N: 0.45 kg kg⁻¹; AE_N: 24.2 kg kg⁻¹) and wheat (RE_N: 0.34 kg kg⁻¹; AE_N: 34.0 kg kg⁻¹) (Lhada et al., 2005) by determining crop N requirements and the N_{min} status of soil before fertilizer application.

Despite these positive results, this research also showed restrictions of the N_{min} based system, when applied to previously over-fertilized fields, as the mineralization of N in soils is not taken into account. In order to put the following discussion into perspective, it is necessary to briefly summarize the N dynamics in this farmer's field as previously published (Hartmann et al., 2014). This particular double-cropping system is characterized by extremely high soil activity during the summer vegetation-period of maize, due to high temperatures and rainfall events (Section 2.1) and very low activity during the vegetation period of wheat, when temperatures are low and no rainfall occurs. The mineralization of both wheat and maize residues therefore occurs mainly during the late spring and summer, leading to high rates of N mineralization, or re-supply.

As the results of the CK treatment, as well as the FP_{CK} treatment in 2011 (Table 2) show, this mineralization of N during the summer-vegetation period meets N demand of the summer-crop, when the field was previously managed according to FP. As Tremblay et al. (2012) and Cui et al. (2008b) observed, the response of cereal crops to fertilizer application is strongly affected by soil N supply, i.e. the yield response to fertilization is reduced at higher N_{min} contents of the soil. The results of this research show that a response in yield to fertilization is evident for winter-wheat. In contrast, the inherent N supply in a previously over-fertilized field effectively prevents a yield-response of maize to additional fertilizer N.

Therefore, while the N_{min} based system does lead to lower N application rates compared to current FP, further reductions should be possible if the mineralization potential of soils in the NCP, especially over the summer-vegetation period, were taken into account.

Based on the results of this research, the N application for wheat is necessary in order to maintain the yield potential of this important crop. Therefore, a controlled system of N application is advisable. For summer-maize, in contrast, mineralization of N during the summer vegetation period must be taken into account. In order to reduce N loss, application rates should not exceed the expected removal of N in harvested grain, until the inherent N supply of previously over-fertilized fields is reduced.

4.2. Evaluation of N fertilizer strategies

As was described above (Table 1), adjustments were made to the timing of N application. Current farmers' practice involves the application of significant amounts of fertilizer N at the 4–6 leaf

stage of maize, as well as the sowing and regreening of wheat. In contrast to FP and similar research projects in the area (Cui et al., 2008a; Meng et al., 2012), the application of fertilizer N at the sowing of wheat was deemed unnecessary, as the N requirements of wheat until regreening should be minimal. As the results of this experiment show, the omission of fertilization in the optimized treatments did not reduce the wheat yield of these treatments in comparison to FP.

When comparing the optimized fertilizer treatments, it is important to note that each fertilizer strategy is preferable to current FP, solely because N application rates were strongly reduced, which must be the main objective of Chinese agriculture at this point of time (Li et al., 2007; Zhao et al., 2007; Ju et al., 2009).

Comparing UREA_{SPLIT} and UREA, where fertilizer was broadcast on the soil surface, there does not appear to be a benefit in split applications of N in terms of yield or N use efficiency. The argument in favor of frequently controlling the N_{min} status of the soil and separating N application is that more applications at lower N rates will reduce N loss through leaching and volatilization, lead to lower total application rates of N, or alternatively improve grain yield (Chen et al., 2011; Meng et al., 2012). Even though that is possible, it must be considered that the frequent analysis of soil fertility and N application would be a considerable effort for farmers in the NCP. As the short-term goal must be maintaining current grain yields while reducing N inputs, a fertilizer strategy involving single, optimized applications of urea is more feasible.

As a possible alternative to urea as N source, ASN_{DMPP} shows great promise in terms of grain yield and N use efficiency. While the input of N over 5 vegetation periods did not significantly differ from the remaining optimized treatments, it achieved the highest grain yield as well as AE_N (Fig. 2). Even though the results did not significantly differ from the remaining fertilizer treatments, there is an indication that the use of stabilized fertilizers such as ASN_{DMPP} may help in achieving higher grain yields in cereal crops. Previous research on the use of NI has shown that the addition of DMPP to ammonium-based fertilizers increased the grain yield of both maize and wheat by 0.25 Mg ha⁻¹ (Pasda et al., 2001), which is approximately the yield increase observed in these experiments, even though the variability of the data prevents a definitive statement.

It is unlikely, though, that such fertilizers will be widely used in traditional farming systems of the NCP. The price of urea remains low due to government subsidies (Ju et al., 2009) and farmers would not benefit financially from using costlier, stabilized fertilizers. A further disadvantage may be the increased risk of ammonia volatilization when stabilized, ammonium-based fertilizers are applied to soils with a high pH.

The results of this experiment do not indicate that UAN is a suitable alternative to urea as N source at this point in time. Even though there were positive results in terms of N recovery, there is no clear advantage when compared to a reduced application of UREA or ASN_{DMPP}. Another disadvantage is that fairly advanced equipment, which is not available to farmers in the NCP, is necessary in order to efficiently apply liquid N fertilizers.

In contrast to UAN, the sub-surface, banded application of urea is easily achievable in small fields of the NCP, using a slightly modified seeding machine that is commonly available to farmers. Even though the results do not clearly indicate an advantage compared to the broadcast application of UREA or ASN_{DMPP} in terms of yield or N use efficiency (Fig. 2), the mechanized, sub-surface application of UREA has benefits. By experience, it is less time-consuming and easier to achieve a uniform application of N compared to fertilization by hand. Further, although not subject of this experiment, the potential of gaseous N loss, as well as leaching is reduced when ammonium-based fertilizers are applied as shallow bands in the soil (Lhada et al., 2005).

Weighing the needs of Chinese agriculture, with regards to maintaining or even increasing the yield of cereal crops while reducing N application rates, a stabilized method of N application, either through the use of NI or through the sub-surface application of urea must be considered. At the very least, N application rates must be adjusted and not exceed N demand of the double cropping-system.

5. Conclusion

With regards to the main hypotheses of this report, the presented results confirm that the reduction of N application rates according to crop demand and soil mineral N status are applicable in intensively cultivated farmers' fields, without reducing the yield in a summer-maize/winter-wheat double cropping system, thereby reducing the over-application of N and increasing both recovery efficiency and agronomic efficiency of N.

The reduction of fertilizer N is possible even with a single application per crop. A frequent control of the soil N_{min} status, as well as the split application of urea shows no advantages either for summer-maize or winter-wheat.

Further reductions in N application rates could be achieved in the NCP, if the mineralization potential of soils were taken into account. The resupply of N to subsequent crops has previously been described in literature. The results of this research indicate that there is no definitive agronomic response of summer-maize to N application for a period of up to two years, following periods of intensive N input as seen in farmers' practice. Further research is needed in order to clearly evaluate the rate of N supply during the summer-vegetation period of a double-cropping systems of the NCP, even though this is difficult to predict in the field and must therefore make use of region-specific soil-dynamics models.

Further, this research shows that the chemical stabilization of ammonium-based fertilizers, either through the use of DMPP or through the concentrated, sub-surface application of N, may increase yields and N use efficiency in this agricultural system. ASN_{DMPP}, as used in this experiment, continuously achieved high yields, and may be an alternative to the commonly used urea, even though the higher cost of such products may limit acceptance. As an alternative, application techniques for the sub-surface application of urea should be pursued, in order to minimize the risk of N loss through leaching or through gaseous loss after N application.

Acknowledgements

This research was jointly funded by the German Federal Ministry of Education and Research (BMBF, Project No. 0330800E) and the Chinese Ministry of Science and Technology (MOST, Grant No. 2007DFA30850). We would also like to express our gratitude to EuroChem Agro, for supplying the Entec product and assisting our research. We would further like to thank our scientific partners both in Germany and China, as well as the laboratory staff without whom this research would not have been possible. Further, we would like to thank the working group of Prof. He Xiongcu, China Agricultural University, especially Dr. Du Wenying, for their machine for the subsurface application of solid N fertilizers.

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Nitrogen dynamics, apparent mineralization and balance calculations in a maize - wheat double cropping system of the North China Plain

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Field Crops Research (2014) 160: 22 - 30
DOI 10.1016/j.fcr.2014.02.014

Reprinted from Field Crops Research, 160, Hartmann, T.E., Yue S.C., Schulz, R., Chen X.P., Zhang F.S., Müller, T.: Nitrogen dynamics, apparent mineralization and balance calculations in a maize - wheat double cropping system of the North China Plain, 22 – 30, 2014, with kind permission from Elsevier.



Nitrogen dynamics, apparent mineralization and balance calculations in a maize – wheat double cropping system of the North China Plain



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ARTICLE INFO

Article history:

Received 2 October 2013

Received in revised form 21 February 2014

Accepted 23 February 2014

Available online 22 March 2014

Keywords:

North China Plain

N surplus

Apparent N loss

Urea

Ammoniumsulphate nitrate

DMPP

ABSTRACT

The aim of this study is to observe the N balance of a summer-maize/winter-wheat double cropping system of the North China Plain (NCP), using data from a static field experiment that was conducted in a previously over-fertilized farmer's field. Two reduced N treatments that were fertilized by adjusting N supply to crop N demand (UREA: urea; ASN_{DMPP}: ammoniumsulphate nitrate + 3,4-dimethylpyrazolophosphate) are compared to common farmers' practice (FP: urea, 550 kg N ha⁻¹ a⁻¹) and to a control treatment (CK). Further, this research aims to estimate the importance of N mineralization for N supply in an intensive maize/wheat cropping system in order to better understand seasonal N dynamics in an over-fertilized system.

The results of the experiment show that the N surplus (fertilized N – grain N) as well as the N balance (N Input – N Output) after harvest are significantly lower for the optimized treatments (Surplus: –25 kg to 98 kg N ha⁻¹; Balance: –36 to 102 kg N ha⁻¹) compared to FP (Surplus: 156 kg to 187 kg N ha⁻¹; Balance: 56–262 kg N ha⁻¹). This leads to lower residual N in the soil horizon from 0 to 90 cm in the reduced treatments (113 kg N ha⁻¹ at end of experiment) compared to FP (293 kg N ha⁻¹).

Mineralization of N, which occurs mainly in the spring vegetation period of wheat and during the summer vegetation period of maize, plays a substantial role in N supply to the summer-crop. Apparent net N mineralization of the CK treatment was 161 kg N ha⁻¹ for the first vegetation period of maize in 2009, decreasing to 27 kg N ha⁻¹ over the following two vegetation periods. The two intermittent periods of winter-wheat showed an apparent net mineralization of 64 and 84 kg N ha⁻¹, that did not influence yield formation. It is therefore likely that N mineralized during the spring vegetation period is carried over to the following vegetation period of summer-maize. In contrast to the CK treatment, an apparent net N loss was determined for all vegetation periods of summer maize in the FP treatment and for the first two vegetation periods of maize in the reduced treatments, even though mineralization in excess of the CK treatment was observed in an *in situ* mineralization experiment.

The results show that the N balance in previously over-fertilized farmers' fields of the NCP can be reduced by estimating crop N demand. Further, mineralization of N is an important factor both for N supply of crops, as well as for the loss of N during the summer vegetation periods and must be taken into consideration if N application rates in the NCP should be further reduced.

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1. Introduction

The North China Plain (NCP), as the main production area of cereal crops in China, has been subjected to an intensification of agricultural production, which at first led to a continuous increase in grain yield through the availability of synthetic fertilizers and higher yielding crop varieties, but also to an increase in fertilizer consumption (Zhu and Chen, 2002). This development has caused an overall reduction in nitrogen (N) use efficiency (NUE), and increased losses of reactive N to the environment. The highest

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gaseous losses in China in form of NH_3 and N_2O have been observed in the NCP, where a combination of over-fertilization, the use of urea as main N source and the soil type encourage volatile losses of reactive N (Ramos, 1996; Subbarao et al., 2006).

A further effect of excessive fertilizer application is the loss of NO_3^- by leaching, which is aggravated through the common practice of flood irrigation as well as the monsoon influenced rainfall pattern of the NCP (Li et al., 2007; Ju et al., 2009).

It has been evident for some time that the input of reactive N to agricultural systems in the NCP must be reduced in order to counter negative effects of N loss to the environment.

A reduction of N loss to the environment may be achieved mainly by increasing the uptake capacity of crops through breeding (Raun and Johnson, 1999), stabilizing N in the soil through chemical nitrification inhibitors such as 3,4-dimethylpyrazole phosphate (DMPP) (Zerulla et al., 2001; Ding et al., 2011) or through innovative application techniques, or, which may be the simplest and quickest measure, reducing application rates of fertilizer N (Lhada et al., 2005).

Recent research has shown that the input of synthetic N fertilizers can be reduced without affecting the grain yield of cereal production of the NCP, thereby increasing NUE, and reducing the potential of N losses to the environment (Chen et al., 2004; Meng et al., 2012). The approach used is an adjusted method for the estimation of crop N requirements, and the consideration of soil mineral N (N_{\min}) status of the soil before fertilization (Wehrmann and Scharpf, 1979; Chen et al., 2006). These methods allow for a reduction of fertilizer N input by up to 50% compared to current farmers' fertilizer practice.

Due to the history of over-fertilization in the area, farmers' fields became overloaded with N, and a large amount of N is cycling within the system through the mineralization of organic matter (Cui et al., 2008c), which, in addition to added fertilizer, is a major part in the N supply of crops. An understanding of the processes involving the mineralization of N may therefore give the possibility of further decreasing application rates of fertilizer N, thereby decreasing the potential for N losses to the environment.

The focus of this report are the dynamics of N in an intensive maize-wheat double cropping system of the NCP, as affected by the adjustment of N application rates. In contrast to most previous research (Chen et al., 2004; Cui et al., 2008c; Meng et al., 2012) that observes the effect of reduced N application over single crops, this report observes N dynamics over consecutive vegetation periods of a maize-wheat cropping system in a field with a high inherent N level, as is representative for agriculture in the NCP.

The objective of the experiments was to identify how fertilizer strategies influence soil N turnover in a farmer's field, and to determine in which vegetation periods measures for reducing the possible loss of fertilizer N and mineralized N must be taken. The aim is to integrate these findings into fertilizer recommendations for farmers in the NCP, in order to reduce environmental damages caused by excess fertilization of N.

The research questions at the onset of this experiment were that (1) using an N_{\min} -based method for the calculation of N application rates will reduce the N surpluses from fertilizer N and the N balance compared to current farmers' practice. (2) The reduced application rates of N will lead to significantly lower concentrations of mineral N in the soil profile compared to farmers' practice. And that (3) the use of stabilized ammonium-fertilizers (ammonium sulphate nitrate + 3,4-dimethylpyrazole phosphate) will reduce the N surplus in the field, and show lower concentrations of N_{\min} in the soil profile compared to urea. Over the course of the experiment, high yields of summer-maize were observed in the CK treatment. The following research questions were therefore considered: (4) The mineralization of N is an important factor of N supply to crops in the NCP. (5) N is released mainly in the summer period of vegetation,

where temperatures and precipitation favor the turnover of N in the soil. Finally (6) N released in the spring vegetation period does not influence yield formation of winter-wheat, but is "carried over", adding to the N supply of the summer-crop.

2. Materials and methods

2.1. Study site

The experiment was carried out in a summer-maize/winter-wheat double cropping system close to the experimental research station of the China Agricultural University in Quzhou County, Hebei Province, PRC (115° E, 36° N, 40 m a.s.l.) in the geographical region known as the North China Plain. The soil of the experimental site is classified as a Cambisol with a silt loam texture according to IUSS Working Group WRB (2007). The soil shows total C concentration of 1.8%, a total N concentration of 0.1% and 110 mg (P) kg (soil)⁻¹. The pH of the soil (CaCl₂) is 7.5. The weather pattern is described as a monsoon influenced steppe climate, with the mean temperature and precipitation at the study site between of 13.6 °C and 490 mm (1980–2009), respectively. About 60% of precipitation occurs between July and September.

The farmer's field chosen for this study had previously been managed as a summer-maize/winter-wheat double-cropping system common in the area, with an annual N fertilization rate of about 550 kg (N) ha⁻¹. Before the onset of the experiment, the farmer was persuaded to omit spring fertilization of wheat (150 kg N ha⁻¹), in order to reduce N_{\min} concentrations in the field.

2.2. Experimental design

The results presented in this paper are part of a research experiment that was conducted in the NCP, PRC, from June 2009 to October 2011. The experiment comprised eight N treatments, with four replicates. The experiment was laid out as a Latin rectangle, all treatments being randomly distributed among each block and row. The plots were 68 m² in size, and separated by 15 cm high earthen dams to allow flood irrigation of the plots. The four experimental blocks were further separated by a 1 m wide walkway for access to the individual plots.

2.3. Treatments

The 4 N treatments presented here were chosen for the calculations of apparent N mineralization (ANM), apparent N loss or gain (ANL/G) as well as the N surplus from fertilizer N application and the N balance of each crop (Table 1). These comprise the Control (CK) treatment without N fertilization and farmers practice (FP), as well as two treatments, reduced urea (UREA) and ammonium-sulphate-nitrate + dimethylpyrazolophosphate (ASN_{DMPP}), for which the N application rate was determined through the calculation of crop demand and the N_{\min} status of soil before fertilizer application. The application rate of N was calculated from yield expectations for wheat and maize in the region, and from N_{\min} at a depth of 0–90 cm. For both maize and wheat, the N demand over the vegetation period was calculated as 200 kg (N) ha⁻¹ at yield expectations of 8–10 Mg (grain) for maize and 8 Mg (grain) ha⁻¹ for wheat, respectively.

The determination of soil N_{\min} was carried out 2 days before fertilization. Soil samples from each treatment were immediately processed and nitrate-N was measured to determine the N_{\min} concentrations of soil (kg N ha⁻¹).

2.4. Field management

Field management, apart from N application, followed current farmers' practice as observed in the region. Maize (cultivar

Table 1
N application rates and technique of the four treatments as applied over the double cropping system. All treatments, including the Control (CK), were side-dressed with 30 kg N ha⁻¹ as 15–15–15 NPK. For the UREA and ASN_{DMPP} treatments, application rates were calculated by subtracting mineral N (N_{\min}) in soil (0–90 cm) measured at the beginning of vegetation in spring time from a target value (200 kg N ha⁻¹) representing a harvest expectation of 8–10 Mg ha⁻¹ for maize and 6–8 Mg ha⁻¹ for wheat.

Treatment	Maize		Wheat		Method	Fertilizer
	Applications No.	N rate kg (N) ha ⁻¹	Applications No.	N rate kg (N) ha ⁻¹		
CK	–	30	–	–	–	Urea
FP	1	250	2	300	Broadcast	Urea
UREA	1	200 – N_{\min}	1	200 – N_{\min}	Broadcast	Urea
ASN _{DMPP}	1	200 – N_{\min}	1	200 – N_{\min}	Broadcast	Urea (30 kg N to maize) + ASN with DMPP (rest)

“Zhengdan”) was sown at a density of ca. 75,000 seeds ha⁻¹ in the middle of June, with a below-ground side-dress of 30 kg (N) ha⁻¹ applied as 15–15–15 NPK compound fertilizer. As maize seed and NPK fertilizer were applied in one step by the same machine, all treatments, including CK, were fertilized accordingly. Depending on rainfall events, the field was flood-irrigated after sowing. Fertilization of maize was carried out at the 4–6 leaf stage. FP was fertilized with 250 kg N ha⁻¹, while the rate of N application for UREA and ASN_{DMPP} was determined as described above. After the harvest of maize by hand in the beginning of October, plant residues were trimmed using a threshing machine, the cut portions being left in the field, before basic fertilization (120 kg (P₂O₅) ha⁻¹, 90 kg (K₂O) ha⁻¹) for the subsequent winter-wheat crop was applied. For FP, 150 kg N ha⁻¹ were additionally applied as Urea. The field was then plowed to a depth of 20 cm and rotary-cultivated to prepare the seed bed for the subsequent crop, winter-wheat (cultivar “Liangxing99”), which was sown at a row spacing of 15 cm and subsequently flood irrigated. At the regreening of wheat in spring, the main fertilization of wheat was carried out. 150 kg N ha⁻¹ were applied to the FP treatment. The application rates for treatments UREA and ASN_{DMPP} were calculated as described above. After the machine harvest of wheat in June, chopped plant residues remained on the soil surface.

2.5. Soil analysis

N_{\min} was determined for each layer separately at 0–30, 30–60 and 60–90 cm depth. At least 5 sample cores were taken per plot, homogenized and passed through a 0.5 mm ϕ sieve. Water content of the samples was determined gravimetrically before the soil samples were extracted with 0.01 M CaCl₂. For the calculation of N_{\min} before fertilization, nitrate was determined reflectometrically using nitrate test-strips (Merck Millipore, RQeasy quick-test). For the calculations presented here, samples were analyzed for NO₃⁻-N and NH₄⁺-N by continuous-flow auto-analysis (SEAL QuAAtro).

2.6. Yield determination

Grain yield of maize was determined through manual harvest of a 10.8 m² sample in the center of the individual plots. Sub-samples were taken for the determination of grain water-content and grain N and C. Plants from the sample area were used for biomass estimation, and the determination of plant water content and plant N and C concentration.

The yield of wheat was determined using 3 samples of each 1 m². Grain and plant material were separated, and sub-samples of the grain and plant material were further processed for the determination of water-content and grain and plant N and C.

2.7. Plant analysis

Grains and plant material were prepared for analysis through 24 h oven-drying at 60 °C and homogenization using a rotating-disk

mill. N and C contents were determined by high-temperature combustion and subsequent gas analysis (Dumas processing) (Elementar Analysensysteme GmbH, Vario MAX CN).

2.8. Calculation of N surplus and N balance

The N surplus from fertilizer N application was calculated for each crop as the difference between applied fertilizer N (N_F) and N removed from the field in the harvested grain (N_G), using a simple balance calculation, the gaseous loss as well as the atmospheric deposition of N were not included in these calculations in order to reduce the degree of error:

$$N \text{ Surplus} = N_F - N_G \quad (1)$$

The N balance for each crop was calculated as the difference between N inputs (In) and N outputs (Out):

$$N \text{ balance} = \text{In} - \text{Out} = (N_F + N_{R \text{ IN}}) - (N_G + N_{R \text{ OUT}}) \quad (2)$$

where $N_{R \text{ IN}}$ is N contained in the residues of previous crop and $N_{R \text{ OUT}}$ is N contained in the harvested crop's residues.

2.9. Apparent net N mineralization

Apparent net N mineralization (ANM) of the control (CK) was calculated as the difference between N recovered at harvest and N supplied at the beginning of vegetation. $N_{\text{recovered}}$ was calculated as the sum of N determined in grain and plant residues and N_{\min} at harvest. N_{supplied} was calculated as the sum of fertilized N and N_{\min} at the sowing of the crop (Cabrera and Kissel, 1988; Fink and Scharpf, 2000; Olf et al., 2005; Cui et al., 2008c):

$$\text{ANM} = N_{\text{recovered}} - N_{\text{supplied}} = (N_G + N_{R \text{ OUT}} + N_{\min \text{ END}}) - (N_F + N_{\min \text{ START}}) \quad (3)$$

where N_G is N contained in the harvested grain, $N_{R \text{ OUT}}$ is N contained in the harvested crop's residues, $N_{\min \text{ START}}$ and $N_{\min \text{ END}}$ are soil mineral N (0–90 cm) at sowing and harvest, respectively, and N_F is applied fertilizer N. The calculations were made for each of the 5 crops that were grown during the experimental period. Further, the calculations were made for three separate phases of the double-cropping system: the summer vegetation phase being the entire duration in which summer-maize was grown (June–October); the winter phase being the period between the sowing and regreening of winter-wheat (October–March); the spring vegetation phase being the period between the regreening (March–June) and harvest of winter-wheat.

2.10. Apparent N loss/gain

The (ANL/G) was calculated for each of the 5 crops grown during the experiment, using the N balance equation described by Zhao et al. (2006) and Cui et al. (2008c), estimating N gained through mineralization in excess of N mineralized in the CK treatment, or,

as the case may be, lost over the course of the cropping period.

$$\text{ANL/G} = N_{\text{recovered}} - N_{\text{supplied}} = (N_G + N_{R\text{OUT}} + N_{\text{min END}}) - (N_F + N_{\text{min START}} + \text{ANM}) \quad (4)$$

where AN is the apparent net N mineralization of the CK plot (calculation 3), N_G is N contained in the harvested grain, $N_{R\text{OUT}}$ is N contained in the harvested crop's residues, $N_{\text{min START}}$ and $N_{\text{min END}}$ are soil mineral N (0–90 cm) at sowing and harvest, respectively and N_F is fertilizer N.

2.11. *In situ* incubation experiment

In order to evaluate the mineralization of N in the upper 30 cm of soil under field conditions, an *in situ* incubation experiment was carried out during the winter-wheat vegetation period of 2010–2011 and the summer-maize vegetation period of 2011. Soil from each plot of the treatments CK, FP and UREA were checked for moisture and N contents, loosely mixed and placed in plastic ziplock bags aiming to retain moisture of the soil while allowing gas exchange. The prepared soil samples were buried together in the center of the field at a depth between 15 and 25 cm at the sowing of the respective crops. At the end of each of the above described phases, the packets were removed from the field and analyzed for soil moisture and nitrate content as previously described.

2.12. Statistical analysis

The experimental results were analyzed using the R programming environment for statistical computing (R Development Core Team, 2011). Experimental data was subjected to Fisher's test for Least Significant Difference (LSD), at a confidence interval of $\alpha = 0.05$.

3. Results

3.1. Grain yields

The yields of the two reduced treatments were equal to or significantly higher than the yield of the FP treatment over the duration of the experiment for both maize and wheat. The grain yield of the CK treatment was significantly reduced compared to the fertilized treatments for both winter-wheat crops, but only for the last summer-maize crop in 2011 (Table 2).

3.2. N surplus and balance

In all vegetation periods of maize and wheat the largest input factor of N was through the application of fertilizer (Table 1) with the exception of the winter-wheat period of 2009–2010, where the input of N through the previous crops residues exceeded N applied through fertilizer. The highest total N inputs ($N_F + N_R$), were observed for the winter-wheat vegetation period of 2009–2010, where a maximum of 443 kg N ha⁻¹ (FP) were brought into the field. The N inputs of both the UREA and ASN_{DMPP} treatments were highest in the first two cropping seasons of the experiment (230 and 230 kg N ha⁻¹ for summer-maize of 2009; 249 and 245 kg N ha⁻¹ for winter-wheat of 2009–2010 (Fig. 1).

N contained in the harvested grain was similar for all fertilized treatments, reflecting the grain yields achieved over the course of the experiment (Table 2), while there were large differences between N contained in the residues of the FP treatment compared to UREA and ASN_{DMPP} (Fig. 1). The maximum output (N_{BIO}) was determined for ASN_{DMPP} at 266 kg N ha⁻¹ for the summer-maize period of 2009. The minimum output was determined for UREA at 126 kg N ha⁻¹ for the summer-maize period of 2011.

For all the observed vegetation periods the highest positive N surpluses ($N_F - N_G$) and N balances (Input – Output) were determined in the FP treatment. The maximum N surplus of 187 kg N ha⁻¹ as well as the highest N balance of 262 kg N ha⁻¹ were observed after the winter-wheat harvest of 2009–2010 (Fig. 1).

Both N surpluses and N balances of treatments UREA and ASN_{DMPP} were comparable to each other throughout the experiment and with the exception of the N surpluses after both winter wheat periods of 2009–2010 and 2010–2011, where the values calculated for ASN_{DMPP} were lower compared to those of UREA, no significant differences between the treatments were observed.

The highest N surplus of 98 kg N ha⁻¹ was calculated for UREA after the summer-maize harvest of 2009, the lowest value of -25 kg N ha⁻¹ was calculated for ASN_{DMPP} after the harvest of winter-wheat in 2010. The highest N balance of 102 kg N ha⁻¹ was calculated for UREA after the winter-wheat period of 2009–2010. The lowest value of -36 kg N ha⁻¹ was calculated for ASN_{DMPP} after the harvest of summer-maize in 2009.

For the CK treatment, the N surplus and N balance calculations showed mostly negative results with the exception of the N balance after the winter-wheat period of 2009–2010 (73 kg N ha⁻¹), where the input of N through the previous crop's residues exceeded N removed in above-ground biomass (Fig. 1).

3.3. N dynamics in 0–90 cm of soil

30 kg N ha⁻¹ N_{min} were determined in the upper 90 cm of soil at the beginning of the experiment, after the farmer had been asked to omit spring fertilization of wheat (150 kg N ha⁻¹) on the field that was used for this experiment. In the FP treatment, the N_{min} concentration in the soil increased to 370 kg N ha⁻¹ after one year (two crops). A reduction of N_{min} was observed in the summer vegetation period of 2010 as well as the spring and summer vegetation period of 2011. At the conclusion of the experiment in October 2011, FP showed N_{min} values of 293 kg N ha⁻¹, while N_{min} of both UREA and ASN_{DMPP} treatment showed values of 113 kg N ha⁻¹ (Fig. 2A).

Over the experimental period, the N_{min} concentrations of treatments UREA (Reduced) and ASN_{DMPP} (ammoniumsulphate nitrate + 3,4-dimethylpyrazole phosphate) reached maximum concentrations of 130 and 110 kg N ha⁻¹, respectively, with similar reductions of N_{min} in the summer vegetation periods of 2010 and 2011. The N_{min} concentrations of treatment CK remained at approximately 30 kg N ha⁻¹ over the entire course of the experiment (Fig. 2A).

Seasonal variations of N_{min} concentrations in the upper 90 cm of soil are reflected in the two upper soil layers from 0 to 30 cm (Fig. 2B) and 30–60 cm (Fig. 2C) for all fertilized treatments.

In contrast to the two optimized N treatments (UREA and ASN_{DMPP}), a steady increase in N_{min} – concentration was observed in the soil horizon from 60–90 cm of the FP treatment (Fig. 2D).

3.4. Apparent net N mineralization (ANM) in the control treatment

In the first period of summer-maize 2009, ANM (Eq. (3)) was highest at 161 kg N ha⁻¹. ANM of the maize vegetation period reduced in the following periods, showing an ANM rate of 75 and 27 kg N ha⁻¹ in 2010 and 2011, respectively. ANM over the winter-wheat period was determined as 64 and 86 kg N ha⁻¹ for 2010 and 2011, respectively (Table 3).

The calculation of ANM for three separate phases of the double-cropping system, namely the (1) summer vegetation period of maize, the (2) winter period of wheat and the (3) spring vegetation period of wheat, shows that mineralization over the summer-maize period in the control treatment continuously decreased over the

Table 2
Harvested grain in Mg ha^{-1} for the four treatments as observed over the duration of the experiment. $\pm\text{SE}$ indicates standard error of the mean. Letters behind values indicate significant differences between treatments within one cropping season at $\alpha = 0.05$ (Fisher's LSD).

	SM 2009 $\text{Mg ha}^{-1} \pm \text{SE}$	WW 2010 $\text{Mg ha}^{-1} \pm \text{SE}$	SM 2010 $\text{Mg ha}^{-1} \pm \text{SE}$	WW 2011 $\text{Mg ha}^{-1} \pm \text{SE}$	SM 2011 $\text{Mg ha}^{-1} \pm \text{SE}$
CK	5.7 \pm 0.31 b	1.8 \pm 0.25 c	5.9 \pm 0.23 b	2.8 \pm 0.04 c	3.4 \pm 0.22 c
FP	6.4 \pm 0.24 ab	4.7 \pm 0.10 ab	6.0 \pm 0.06 b	6.0 \pm 0.09 ab	6.3 \pm 0.54 ab
UREA	6.6 \pm 0.16 ab	4.4 \pm 0.09 b	7.2 \pm 0.29 a	5.7 \pm 0.26 ab	6.3 \pm 0.22 ab
ASNDMPP	6.9 \pm 0.33 a	5.6 \pm 0.58 a	6.7 \pm 0.39 ab	6.2 \pm 0.34 a	5.8 \pm 0.45 b

SM, summer maize; WW, winter wheat; CK, control; FP, farmers' practice; UREA, reduced; ASNDMPP, ammonium-sulfate nitrate + DMPP.

three observed vegetation periods, and that mineralization during cultivation of wheat occurs mainly in the spring vegetation period, after re-greening in mid-march. During the winter-period, N_{\min} is reduced, or remains equal compared to N_{\min} determined at the sowing of winter-wheat (Fig. 2A).

3.5. Apparent N loss or gain of fertilized treatments

For the FP treatment, a gain (Eq. (4)) in available N_{\min} in excess of ANM of the control was calculated for the spring vegetation period of 2010 (156 kg N ha^{-1}) and for the winter vegetation period of 2011 (31 kg N ha^{-1}). For the remaining vegetation periods a loss of available N was determined, the highest occurring in the summer-vegetation period of 2010 ($-350 \text{ kg N ha}^{-1}$) (Fig. 3B). For treatment UREA, periods of N gain were determined for the winter and spring vegetation period of 2009–2010 (10 and 19 kg N ha^{-1} , respectively), the winter vegetation period of 2009–2010 (19 kg N ha^{-1}) and the summer vegetation period of 2011 (43 kg N ha^{-1}). For the remaining vegetation periods a loss of N was calculated, the highest occurring in the summer vegetation period of 2010 ($-158 \text{ kg N ha}^{-1}$) (Fig. 3C). For treatment ASNDMPP, periods of N gain and loss were in accordance with those of UREA. The highest N gain was determined for the summer vegetation period of 2011 (43 kg N ha^{-1}), the highest loss of N was determined for the summer vegetation period of 2010 ($-151 \text{ kg N ha}^{-1}$) (Fig. 3B).

3.6. Nitrogen mineralization in the in situ experiment

Soil incubated in the field over the winter-wheat vegetation period of 2010–2011 showed an increase in N_{\min} of 1.1 – $14.6 \text{ mg N kg (soil)}^{-1}$ in soils taken from treatment CK, from 11.8 to $32.5 \text{ mg N kg (soil)}^{-1}$ for FP, and from 3.6 to $26.5 \text{ mg N kg (soil)}^{-1}$ for UREA, resulting in ΔN_{\min} of 13.5 , 20.3 and $22.9 \text{ mg N kg (soil)}^{-1}$ for treatments CK, FP and UREA, respectively (Fig. 4A).

Over the summer maize vegetation period of 2011, N_{\min} of soil from treatment CK increased from 1.4 to $50.6 \text{ mg N kg (soil)}^{-1}$. N_{\min} of soil taken from FP increased from 28.6 to $123.2 \text{ mg N kg (soil)}^{-1}$ and soil from treatment UREA increased from 14.9 to $84.9 \text{ mg N kg (soil)}^{-1}$, resulting in ΔN_{\min} of 49.2 , 94.6 and $70 \text{ mg N kg (soil)}^{-1}$ for the control, FP and UREA, respectively (Fig. 4B).

Table 3
Apparent net N mineralization (ANM) of the control (CK) treatment, as calculated for five vegetation periods of the experiment. $\pm\text{SE}$ indicates the standard error of the mean.

	SM 09 $\text{kg ha}^{-1} \pm \text{SE}$	WW 10 $\text{kg ha}^{-1} \pm \text{SE}$	SM 10 $\text{kg ha}^{-1} \pm \text{SE}$	WW 11 $\text{kg ha}^{-1} \pm \text{SE}$	SM 11 $\text{kg ha}^{-1} \pm \text{SE}$
$N_{\min \text{ START}}$	30 \pm 0	23 \pm 8	33 \pm 3	28 \pm 3	45 \pm 5
N_{F}	30	0	30	0	30
$N_{\min \text{ END}}$	23 \pm 8	33 \pm 3	28 \pm 3	45 \pm 5	19 \pm 2
N_{BIO}	198 \pm 18	54 \pm 6	111 \pm 8	69 \pm 6	82 \pm 10
ANM	161 \pm 25	64 \pm 7	75 \pm 8	86 \pm 9	27 \pm 15

SM, summer maize; WW, winter wheat; $N_{\min \text{ START/END}}$, mineral N in 0–90 cm at seeding and harvest; respectively; N_{F} , fertilized N; N_{BIO} , N in aboveground biomass at harvest; ANM, apparent net N mineralization.

4. Discussion

4.1. N surplus and N balance

The research presented here shows that the adaptation of N application rates to crop demand and mineral N status of the soil, as described Lhada et al. (2005) can reduce both N surplus and balance without affecting the yield level of the cropping system. The N surplus of the optimized treatments was reduced to less than ca. $50 \text{ kg N ha}^{-1} \text{ crop}^{-1}$ for the final four vegetation periods, while N application according to farmers' practice (FP) resulted in N surpluses of above $150 \text{ kg N ha}^{-1} \text{ crop}^{-1}$ for each of the five vegetation periods observed in this experiment. As has been described by several studies (Ju et al., 2006; Raun and Johnson, 1999), N applied in excess of the crops' demand is prone to loss pathways without influencing the yield of crops.

In contrast to the calculated N surpluses, the calculations of the N balance, which take organic N in plant residues into account, show a more differentiated result. Due to the restrictions of the maize/wheat double cropping system of the area, maize is harvested before senescence is completed, and the residues contain larger amounts of N. Therefore, the N balance of the wheat vegetation period is higher compared to the N surplus, while the N balance of the maize vegetation period is lower compared to the N surplus.

In this experiment, we could not determine a clear advantage of stabilized fertilizers (ASNDMPP) in comparison to urea (UREA) with regards to N balance and surplus calculations. While there were differences between the two optimized treatments in terms of N surplus and balance in individual vegetation periods, the results of this experiment do not indicate whether the differences are relevant.

4.2. N accumulation in soil horizons

Reduced application rates of N led to significantly lower concentrations of mineral N in the soil profile compared to FP. Fertilization according to FP resulted in high mineral N concentrations in the soil after harvest, while fertilization according to crop demand and consideration of N_{\min} resulted in N_{\min} concentrations not higher than ca. $100 \text{ kg (N) ha}^{-1}$ throughout the experiment, the value which, in Europe, had been described as an acceptable range of N_{\min} after harvest (Ju et al., 2006; Hofman, 1999). These results are in accordance with other research conducted in the region, which observed

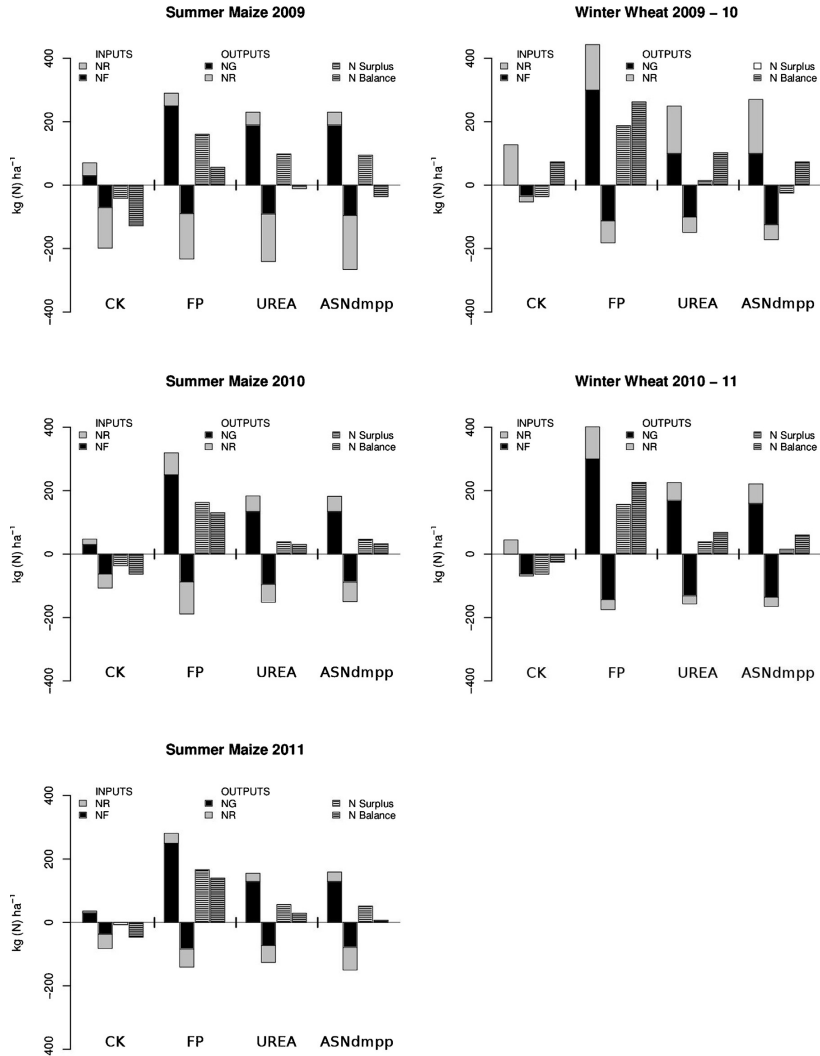


Fig. 1. N Surplus ($N_e - N_c$) and N balance (N Input – N Output) over five vegetation periods as influenced by different strategies of N application (CK: control; FP: farmers' practice; UREA: reduced N; ASN_{DMPP}: ammoniumsulphate nitrate + DMPP; N_R : N contained in plant residues; N_G : N contained in grain; N_F : fertilized N in kg ha^{-1}).

a reduction of residual N_{min} after harvest (Cui et al., 2008b; Meng et al., 2012). Over the course of the experiment, an accumulation of $\text{NO}_3\text{-N}$ in the soil layer from 60 to 90 cm was observed in the FP treatment, but not in either of the optimized treatments (UREA and ASN_{DMPP}), indicating that the downward movement of reactive N was reduced after the adjustment of N application rates. Similar N dynamics in the upper 0–90 cm of soil were observed by Zhao et al. (2006), Cui et al. (2008a) and Fang et al. (2006).

As with the N surplus and N balance calculations, no clear advantage of stabilized N fertilizer (ASN_{DMPP}) in comparison to urea (UREA) was observed in this experiment.

4.3. Apparent net N mineralization

The distinct "anomaly" that was observed in the control treatment (CK) of this experiment was the high yield of summer maize

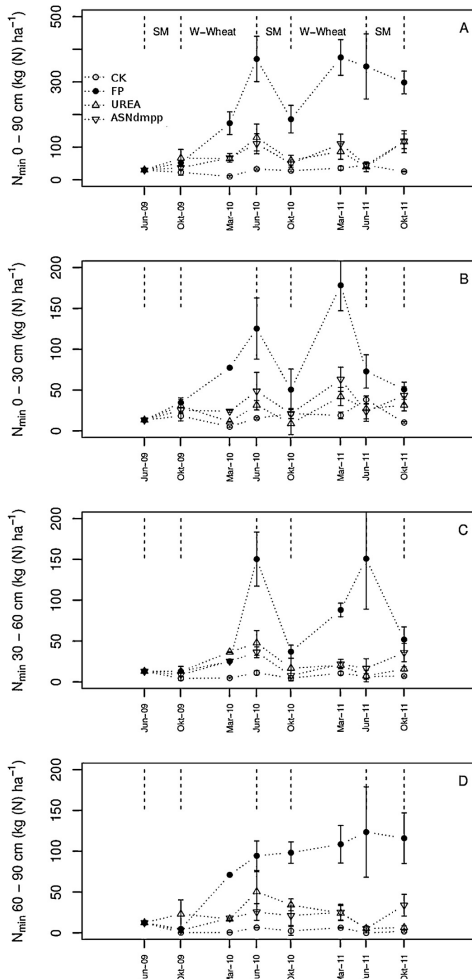


Fig. 2. N_{min} development in (A) 0–90 cm of soil, (B) 0–30 cm, (C) 30–60 cm and (D) 60–90 cm of soil, expressed in kg (N) ha^{-1} following no application of N (CK), farmers' practice (FP, the reduced application of urea (UREA) and the reduced application of ammonium-sulphate nitrate + DMPP (ASN_{DMPP}). Error bars indicate the standard errors of the mean (SE).

in the first two vegetation periods. As described, the N_{min} contents in the soil were low at the beginning of the experiment, which was attributed to the omission of spring fertilization of wheat prior to the beginning of this experiment. In contrast to maize, the intercrop of winter-wheat suffered yield depression.

The calculations for apparent N mineralization in this experiment, based on N_{min} contents of the soil and the accumulation of N in aboveground biomass, indicate that there was a mineralization of N during the summer vegetation period, in decreasing order over

the three cropping seasons of maize, with yield depression being observed in the CK treatment in the final vegetation period. No significant mineralization or loss/fixation of mineral N was observed during the winter vegetation period from October to March, while similar amounts of N appeared over the spring vegetation period from March to June (Fig. 3A).

These calculations are supported by the results of the *in situ* incubation of soil taken from treatments CK, FP, and UREA (Fig. 4), where high mineralization of N was observed in soil from treatment CK over the summer-vegetation period, while only small amounts of N were released during the winter and spring vegetation periods of 2010–2011.

These results are in accordance with accepted theories on N mineralization, as summarized by Lhada et al. (2005): high temperatures and moisture, as is typical for summer-vegetation periods of the NCP, favor the mineralization of organic N pools. In combination with atmospheric N deposition (Ju et al., 2009) mineralization is therefore likely to have contributed to the high yields of maize in the first two seasons of this experiment.

These processes indicate that N contained in the plant residues of maize, which are incorporated in the field before the seeding of wheat, are not mineralized in the winter vegetation period, but only in the spring vegetation period from March to June. As a consequence, N contained in the residues of summer-maize in effect "carries over" to the following summer-vegetation period, where it adds to the N supply of summer-maize. The observations on wheat and maize yield of treatment CK (Table 2), the description of N inputs and outputs (Fig. 1), as well as the observations on mineralization in the *in situ* experiment (Fig. 4) support this argument.

In order to confirm this argument, further experiments on the turnover of N in a wheat/maize double-cropping system are necessary. These should integrate ^{15}N and ^{13}C based studies, as have been described by Lhada et al. (2005) and others. The most suitable approach would be the incorporation of marked maize residues and the analysis of recovery in the following crops of wheat and maize.

4.4. Apparent N loss or gain

In contrast to apparent net N mineralization of the control (CK), the calculations for apparent net N loss/gain of the fertilized treatments show that, with exceptions, the spring and summer vegetation periods are characterized by apparent N loss, which is higher in the FP treatment compared to the optimized treatments. Similar observations were described by Chen et al. (2006).

The results of the *in situ* incubation experiment indicate that mineralization in excess of the control takes place in soils taken from the FP and UREA treatment, which may be explained through the priming-effect of mineral N on the turnover of organic material (Ma et al., 1999). The combination of initial soil N_{min} , mineralization of N and fertilized N leads to an N supply far in excess of crop N demand, which has been explained as a main driving factor for the loss of reactive N (Lhada et al., 2005; Subbarao et al., 2006). The most likely pathways for N loss in this geographical region are the leaching of nitrate into deeper soil-layers, which is supported by the accumulation of N_{min} in the soil horizon from 60 to 90 cm, and through the gaseous loss of N, as described by Cai et al. (2002).

4.5. Recommendation on N application in the NCP

Previous research (Raun and Johnson, 1999; Ju et al., 2006; Lhada et al., 2005; Subbarao et al., 2006) has sufficiently described the negative effects of an over-application of N in agriculture and it is clear that a continuation of FP is untenable. While it is unlikely that a calculation of N application rates based on an N_{min} system can soon be established in the NCP, the results presented here indicate that a reduction of N application rates by up to 50% compared to

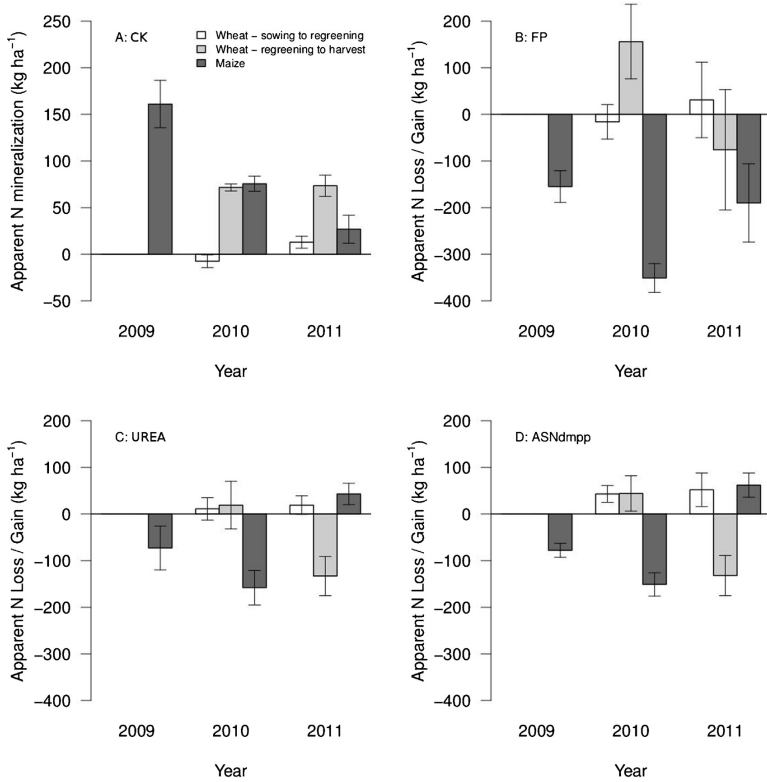


Fig. 3. Apparent N mineralization (ANM) in kg (N) ha⁻¹ of the control treatment (A) and apparent N loss or gain (ANL/G) of farmers' practice (B: FP), reduced N application (C: UREA) and ammonium sulphate nitrate + DMPP (D: ASNdmpp), calculated for 3 separate phases of the double-cropping system, as observed from the start of the experiment in June 2009 until the conclusion of the experiment in October 2011. Error bars indicate standard error of the mean (SE).

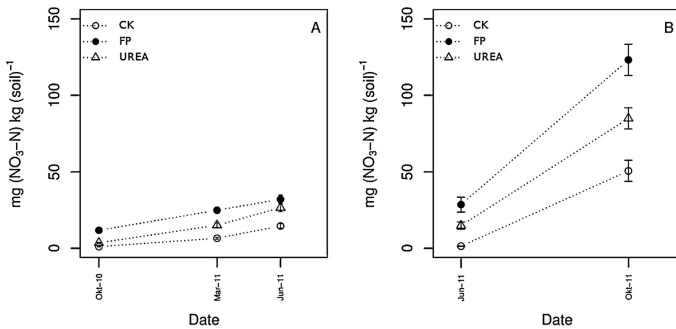


Fig. 4. Nitrogen mineralization in soil taken from 0 to 30 cm of 3 treatments (CK: control, FP: farmers' practice and UREA: reduced) as observed in the *in situ* incubation experiment during (A) winter and spring vegetation phases of 2010–2011 and the (B) the summer vegetation phase of 2011.

FP is possible without negatively affecting the yield of the double-cropping system, while reducing the surplus of N after harvest as well as the accumulation of N in the soil profile.

Further, when addressing N application in a previously over-fertilized field, it is necessary to base recommendations not on the N demand of a single crop, but on the N demand of the entire cropping system, i.e. maize and wheat, as the weather pattern of the NCP affects the turnover of N over the course of a year. In the short-term, N application rates should be based on the expected removal of N through the grain of harvested crops, in order to reduce the N surplus. Due to the dependency of wheat on the application of fertilizer N, as well as the low risk of N loss during the winter and spring vegetation periods it is possible to apply N slightly above crop demand. During the summer vegetation period, when mineralization adds to N supply and the risk of N loss is high, N application rates must be strongly reduced or even be limited to the side-dressing of N at sowing. Once the strong cycling of N in the cropping systems of the NCP has been reduced, it is possible to implement modern approaches toward a higher efficiency of N in the cropping-systems of the NCP.

5. Conclusion

The reduction of N application rates in a maize/wheat double cropping system of the NCP leads to significantly lower N surpluses after harvest, compared to common farmers' practice. This in turn leads to a lower accumulation of mineral N in the soil horizon from 0 to 90 cm, thereby reducing the potential for N loss. Mineralization of N, which mainly occurs during the spring and summer vegetation periods, is an important factor of N supply for summer-maize. Mineralized N from the residues mainly of maize, but also wheat, appears to "carry over" to the following summer vegetation period, and has no, or only little, influence on the yield formation of winter-wheat. The mineralization of N in fertilized plots exceeds that of the control treatment over the summer-vegetation period, adding to the N supply of maize. Nevertheless, a net loss of N is observed in the summer vegetation period. This calculated loss of N is highest in farmers' practice, where N supply strongly exceeds N demand of the crop, and the N surplus after harvest is higher compared to optimized application rates of N.

N application rates must be based on the demand of the entire wheat/maize double cropping system. The emphasis should lie on the supply of N to wheat, which is dependent on fertilization for yield formation, while the application of N to maize must be strongly reduced, as mineralization of N meets crop N demand and the risk of N loss during the summer vegetation period is high.

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Model-based optimization of nitrogen and water management for wheat-maize systems in the North China Plain

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Nutrient Cycling in Agroecosystems (2014) 98: 203 - 222
DOI 10.1007/s10705-014-9606-0

The original publication is available at <http://link.springer.com>

Abstract

The excessive use of nitrogen fertilizer and irrigation water in the North China Plain leads to an accumulation of nitrate in sub-soil and to water pollution. HERMES, a dynamic, process-oriented soil-crop model was used to evaluate the effects of improved nitrate and water management on nitrate leaching. The model was validated against field studies with a winter wheat (*Triticum aestivum* L.)–summer maize (*Zea mays* L.) double-cropping system. A real-time model-based nitrogen fertilizer recommendation (NFR) was carried out for one wheat crop within the rotation and was compared to farmers' practice and soil mineral nitrogen (N_{\min}) content-based fertilization treatments. Consequences of varying irrigation and annual weather variability on model-based NFR and further model outputs were assessed via simulation scenarios. A best-practice simulation scenario with model-based NFR and adapted irrigation was compared to reduced N and farmers' practice treatments and to a dry and a wet scenario. The results showed no differences in grain yield between these simulated treatments. Different fertilizer inputs led to higher nitrogen use efficiency (not significant) of the model-based NFR. Increasing amounts of irrigation resulted in significantly higher N leaching, higher N requirements and reduced yields. The impact of weather variation on model-based NFR was smaller. In the best-practice scenario simulation, nitrogen input could be reduced to 17.1 % of conventional farmers' practice, irrigation water to 72.3 % and nitrogen leaching below 0.9 m to 1.8 % and below 2.0 m soil depth to 0.9 % within 2 years. Model-based NFR in combination with adapted irrigation had the highest potential to reduce nitrate leaching.

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A simplified recommendation for nitrogen fertilization in a wheat / maize double-cropping system in the North China Plain

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*Poster Contribution, Tagung der Deutschen Gesellschaft für
Pflanzenernährung,
Bonn, 2012*

5 A simplified recommendation for nitrogen fertilization in a wheat / maize double-cropping system in the North China Plain

5.1 Abstract

Currently, farmers in the North China Plain (NCP) are fertilizing up to 550 kg (N) ha⁻¹ a⁻¹ in a winter-wheat / summer-maize double cropping system, resulting in a continuous accumulation of N in the soil profile and an increased risk of nitrate leaching and the emission of climate relevant gases. Field experiments showed that N fertilization in these double cropping systems can be reduced by up to 50 % compared to farmers practice without significant reductions in the yield of either maize or wheat. Further, significant yield losses of unfertilized maize could only be observed in the third year of the experiment (chapter 2).

Based on these results we propose a simple and straightforward N fertilization recommendation for a winter-wheat / summer-maize double cropping system in the NCP, which emphasizes the application of N to the winter-crop while reducing input for the summer-crop when mineralization in the soil covers crop N demand.

Using the crop-simulation model HERMES (chapter 4), we evaluated this N fertilization recommendation for effects on plant-growth, yield and possible N losses and compared the results to farmers fertilization practices, a zero N treatment, as well as fertilizer recommendations based on the N_{min} – method.

5.2 Introduction

Up to 550 kg (N) ha⁻¹ a⁻¹ are applied in winter-wheat / summer-maize double cropping systems of the North China Plain (NCP), leading to high N surpluses and an increased risk of gaseous N losses and nitrate leaching.

Due to the sheer amount of farmers in the NCP and the small size of fields, it is difficult to implement and control regulations that aim to reduce N input into agricultural systems.

Therefore, we devised a simple recommendation for the fertilisation of a winter-wheat / summer-maize double-cropping system in the NCP, which was derived on the basis of measured plant N-uptake and N mineralization data. We compared the simple recommendation to a Farmers' Practice (FP) treatment and a fertilizer recommendation based on soil mineral N (N_{\min}) supply using the HERMES model.

5.3 Materials and Methods

5.3.1 Set-up of the HERMES model

The HERMES model was calibrated and validated using data from 2 field experiments carried out in Quzhou, Hebei Province (PRC), and set

to compare four N input treatments. All model parameters were set to take current agricultural practice into account (e.g. flood irrigation; irrigation events after both seeding and fertilization). These parameters were the same for all treatments. In order to obtain realistic results, weather data from 2002 to 2011 was chosen (Quzhou). Gaseous losses were calculated by estimation of fertilizer N losses after application.

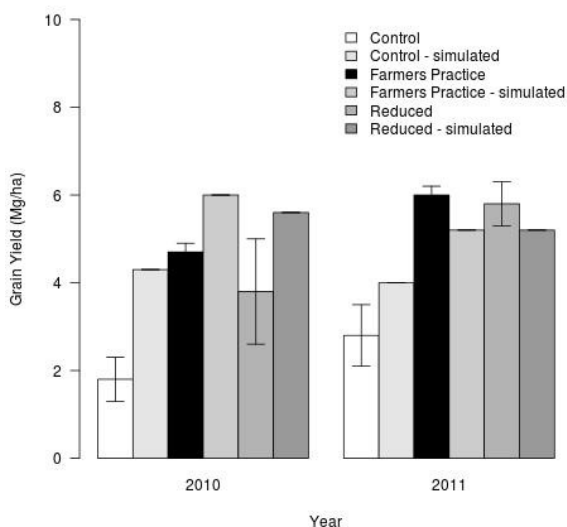


Figure 1: Comparison of measured versus simulated yield of three N-treatments for winter-wheat

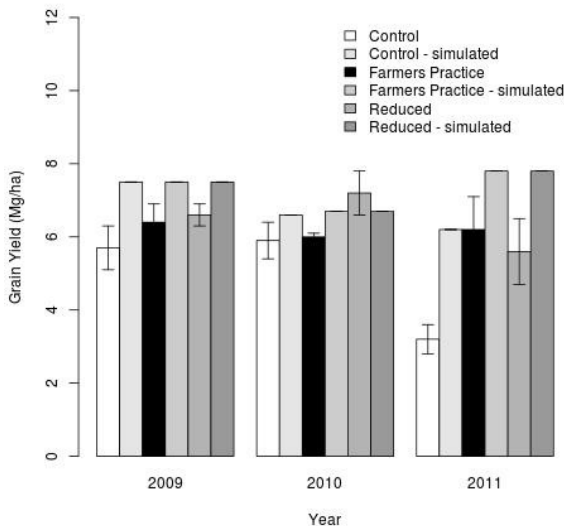


Figure 2: Comparison of measured versus simulated yield of three N-treatments for summer-maize

5.3.2 The simulated N treatments

1. Control

30 kg (N) ha⁻¹, sowing of maize (NPK)

2. Farmers' Practice

150 kg (N) ha⁻¹, sowing of wheat (NPK); 150 kg (N) ha⁻¹, regreening of wheat
30 kg (N) ha⁻¹, sowing of maize (NPK); 250 kg (N) ha⁻¹, 4-6 leaf stage of maize

3. Reduced

200 kg (N) ha⁻¹ – N_{min}, regreening of wheat

30 kg (N) ha⁻¹, sowing of maize (NPK); 200 kg (N) ha⁻¹ – N_{min}, 4-6 leaf stage of maize

4. Simplified N fertilisation for the NCP (Simple)

30 kg (N) ha⁻¹, sowing of wheat (NPK); 150 kg (N) ha⁻¹, regreening of wheat

30 kg (N) ha⁻¹, sowing of maize (NPK); 90 kg (N) ha⁻¹, 4-6 leaf stage of maize

5.4 Results

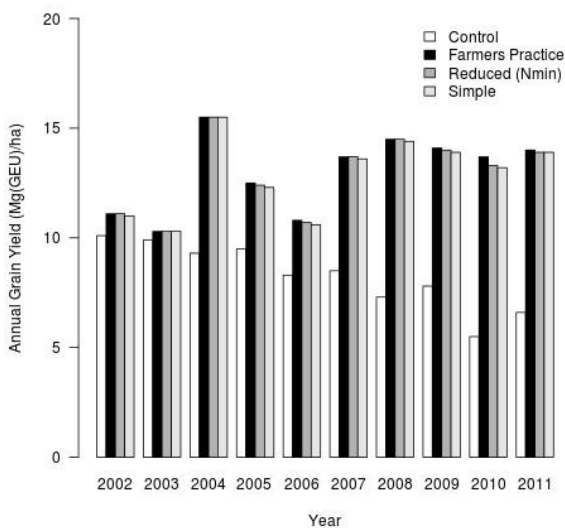


Figure 3: Simulation of annual grain Yield (Wheat + Maize) of four treatments over a ten year period

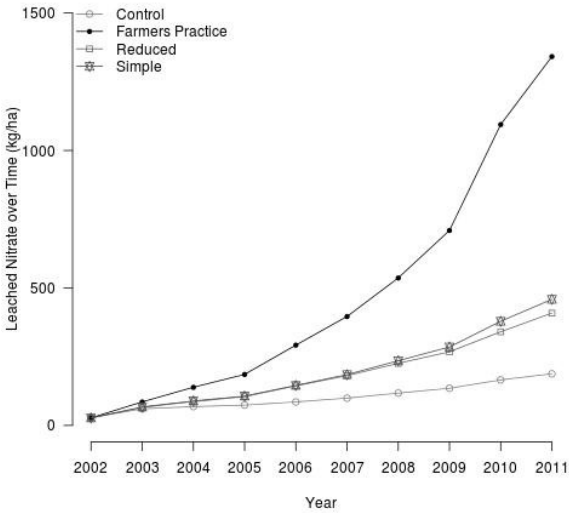


Figure 4: Estimation of leached nitrogen over a ten year period in four considered fertilizer scenarios

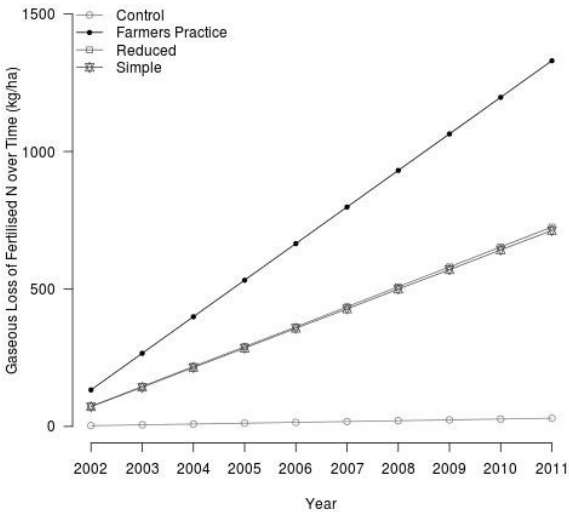


Figure 5: Estimation of gaseous N loss over a ten year period in four considered fertilizer scenarios

These preliminary modelling results show that a simple fertilizer recommendation based on the N demand of the double-cropping system can maintain yields in the mid-term (Figure 3), while reducing the leaching (Figure 4) and gaseous loss (Figure 5) of N compared to farmers' practice.

4.5 Conclusions

- (1) The simulation results indicate that grain yield would not be negatively affected through a reduced (Soil N_{\min}) or simplified application of N.
- (2) The loss of N through leaching and gaseous loss could be greatly reduced simply through the reduction of fertilizer rates.
- (3) Even when weather conditions favour high yields, sufficient N is supplied through reduced and simplified fertilization regimes.
- (4) Field experiments are necessary to validate a simplified fertilizer recommendation, and to further adjust fertilizer recommendations for the NCP.

4.6 References

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The turnover of urea in soil from the North China Plain as affected by wheat straw and the urease inhibitor nBPT

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6 The turnover of urea in soil from the North China Plain as affected by the urease inhibitor NBPT and wheat straw

6.1 Abstract

As urea is applied to predominantly high-pH soils in the North China Plain (NCP), high gaseous losses of N are observed in the forms of nitrous oxide (N_2O) and ammonia (NH_3). In agricultural systems the production of N_2O and N_2 may further be stimulated by the addition of fresh organic materials, as oxygen consumption during respiration favors anaerobic conditions for denitrification processes. The addition of the urease inhibitor (UI) N-(n-butyl) thiophosphoric triamide (nBPT) may restrict the loss of N by reducing the rate of urea-hydrolysis and limiting the substrates for the emission of NH_3 and N_2O . This research investigated the turnover of N, as well as the emission of NH_3 , N_2O and CO_2 as affected by the addition of wheat straw (-/+ wheat straw) and nBPT (- / urea / urea+nBPT) in a two-factorial incubation experiment (20 days, 18°C). There was a significant main effect of straw on nitrate-N and total-N concentrations (without > with wheat straw) as well as on ammonium concentrations (without < with wheat straw) after the addition of both urea and urea+nBPT. Incorporated straw did not significantly affect the volatilization of NH_3 , but increased CO_2 respiration and interacted with urea to increase N_2O emission by a factor of 6.5. nBPT reduced the appearance of NH_4^+ after the application of urea and almost completely prevented the loss of NH_3 . It effectively reduced the rate of urea hydrolysis, but not the rate of nitrification, which has implications on the availability of N from urea for plants. The main observations of this research were that added wheat straw prolonged the appearance of NH_4^+ both after the application of urea and urea+nBPT, while reducing the appearance of nitrate. Wheat straw may therefore either act as a stimulant of hydrolysis or as an inhibitor of nitrification. Urea increased soil respiration and the emission of N_2O , possibly acting as a C and N source for microbial activity as has previously been described. In combination with the application of organic C sources, this effect of urea may be a main driver of gaseous N loss.

6.2 Introduction

Over the last 50 years, the loss of reactive N species to the environment has dramatically increased as more synthetic fertilizers were applied to agricultural systems, thereby drastically changing the global N cycle (Vittoušek et al., 1997). China, as an emerging nation with a declared goal of self-sufficiency, has increased production- and application-rates of synthetic fertilizers in order to increase agricultural production. While yields did initially increase, the discrepancy between N use and N recovery has been widening since the late 1980's and the loss of N to the environment has steadily increased (Mathews, 1994).

Although many single factors contribute to pollution in China, it is the fertilization behavior of farmers and their attitude towards the overuse of chemical fertilizers that has the biggest impact on the loss of reactive N (Ti et al., 2012; Ju et al., 2009; Li et al., 2007).

The main problem with over-fertilization is that the rate of N loss is strongly linked to the over-supply of fertilized N. Additionally, for every metric ton (t) of applied chemical N, a total of 13.5 t of CO₂-equivalents is lost during the production, transportation and application of fertilizer (Zhang et al., 2011).

The most common synthetic N source in China is urea. It is widely available and priced competitively due to China's state subsidies for agriculture. The NCP, where most of China's cereals are produced,

consists of carbonate-rich, medium textured soils. Therefore, the application of urea may not be the best alternative, as urea is not a stable compound. Under normal soil conditions the urease enzyme catalyzes the hydrolysis of urea to ammonia (NH_3) and CO_2 within a few days (Marsh et al., 2005). In (soil-)solution, there is a pH-dependent balance between ammonia (NH_3), a gaseous molecule that is dominant in alkaline environments, and ammonium (NH_4^+). Only the latter is stable in the soil and dominates in acidic environments. Additionally, the formation of hydroxide ions (OH^-), when ammonia is hydrogenated, may lead to a further increase in pH and further increased ammonia volatilization (Watson et al., 1994).

The evidence of ammonia loss from applied urea ranges widely, from 25% over a 20 day period to 30% within 3 days of application (McKinnes et al., 1986; Sommer and Jensen, 1993; Zhang et al., 2013) and it is estimated that 95% of N emissions from crop production in China are in the form of ammonia from urea and ammonium bicarbonate, the second most important N fertilizer in China (Yan et al., 2003).

As ammonia gas reacts with nitric or sulfuric compounds in the atmosphere, it may be subjected to long-range transport and it has been estimated that the reactive N emitted from fields is contributing considerably to the N supply of crops in China in itself (Ju et al., 2009). Besides the hazard of increased ammonia losses, N-fertilization with

urea provides the substrate for nitrous oxide (N_2O) producing microorganisms in soils after hydrolysis and subsequent nitrification of ammonium. N_2O is a potent climate relevant trace gas that accounts for approximately 7.9% of the anthropogenic greenhouse effect (Rogner et al., 2007) and which contributes to stratospheric ozone depletion (Crutzen, 1981). Although some further processes are discussed as a source for N_2O in soils, there is no doubt that nitrification and denitrification contribute substantially to N_2O production in soils (Granli and Bøckman, 1994; Bremner, 1997, Buerkert et al., 2012). Nitrification is the autotrophic oxidation of ammonium in aerobic soil compartments, whereas nitrate is reduced to gaseous nitrogen oxides and N_2 during heterotrophic denitrification in compartments with low oxygen partial pressure. It has been described that both nitrification as well as denitrification processes significantly contribute to the emission of N_2O at lower soil moistures, while processes of denitrification are predominant when high soil moisture leads to anaerobic conditions (Baggs, 2008; Kool et al., 2011). Further, denitrification relies on organic carbon as an electron donator. It has been shown that especially the incorporation of fresh organic materials stimulates N_2O production by favoring the anaerobic conditions for denitrification due to oxygen consumption during the respiration of the easily available carbon (Flessa and Beese, 1994; Parkin, 1987). Especially the combination of NO_3^- and carbon sources such as oat residues resulted in strong

increased N₂O emissions as compared to the control treatments which received only NO₃⁻ or only oat residues (Garcia-Ruiz and Baggs, 2007). The assumption that denitrification was the major N₂O source under such conditions with easily available C and NO₃⁻ was confirmed by Garcia-Ruiz and Baggs (2007) using ¹⁵N tracers. Similar results were reported from Pfab et al. (2012), who found increasing N₂O emissions from a chard field the closer the mineral N fertilization was temporally placed after the incorporation of the preceding green rye. All these results suggest that a reduction of the N₂O emission can be achieved if the temporal availability of C and NO₃⁻ can successfully be decoupled.

One promising approach is using nitrification inhibitors (NIs) because they delay nitrification of ammonium and thus reduce the amount of nitrate therefore lowering the concentration of nitrate serving as a substrate for denitrification. Several investigations showed the potential of NIs to reduce the N₂O emission (Akiyama et al., 2010).

The inhibition of nitrification, however, increases the potential for ammonia volatilization. For the conditions of the NCP, it would be preferable to chemically inhibit the upstream step of urea hydrolysis, thereby maintaining the chemical form of urea until the N compounds are washed into the soil.

A promising chemical agent for the inhibition of the urease enzyme is the chemical compound N-(n-butyl) thiophosphoric triamide (nBPT) which has been shown to reduce the loss of ammonia and thereby

increase the efficiency of urea-based fertilizers on a variety of crops (Watson et al., 1990; Kawakami et al., 2012, Rodrigues Soares et al., 2012).

The research presented here aimed to observe the effect of the urease inhibitor nBPT and the addition of an organic carbon source on the turnover of urea in soil from the NCP, and to observe how these factors affect the loss of reactive N as ammonia and nitrous oxide.

The main hypotheses concerning the use of the urease inhibitor nBPT were that (1) urea + UI (a) shows a reduced rate of hydrolysis, resulting in lower concentrations of ammonium-N in incubated soil compared to urea -UI and (b) subsequently shows results in lower concentrations of nitrate-N; (2) Urea+UI shows reduced volatilization of ammonia-N compared to Urea – UI; and (3) Urea+UI reduces the substrate for denitrification (nitrate-N) leading to lower gaseous emission of N₂O.

Concerning the addition of wheat straw, the main hypotheses were that (1) the addition of wheat straw leads to lower concentrations of mineral-N in incubated soil; (2) the addition of wheat straw leads to an increase in biological activity, measurable through CO₂ respiration; (3) the decomposition of wheat straw increases the emission of N₂O; (4) incorporated wheat straw has no effect on the volatilization of ammonia-N.

6.3 Materials and methods

6.3.1 Soil

The soil used in this experiment was a homogenized sample taken from the Ap horizon of a farmer's field in the NCP (Quzhou County, Hebei Province, PRC, 115 °E, 36 °N, 40 m a.s.l.). According to the IUSS working group WRB (2007) the soil can be classified as a Cambisol with a silt-loam texture. Soil analysis showed a total C concentration of 1.8 %, a total N concentration of 0.1 % and 110 mg (P) kg (soil)⁻¹, and the pH (CaCl₂) was 7.5. Before transport, the soil was air-dried and homogenized after sieving through a 0.5 cm mesh sieve. In order to restore soil activity and avoid a nitrification flush on beginning the experiments the soil water content was adjusted, judged on experience, to 10% (slightly moist) using distilled H₂O and stored in a cold-room at 7 °C for a period of two months.

6.3.2 Wheat straw

The wheat straw used in this experiment was taken from the field experiment previously described. The straw showed a C:N ratio of 70:1. Before transport and analysis, the plant material was oven-dried at 95°C and homogenized using a rotating disc-mill.

6.3.3 Fertilizer

Two N-fertilizers were used in this experiment, the first being pure urea with an N concentration of 46 %, the second being the UTEC[®] product from Eurochem Agro, a urea-based fertilizer with an N concentration of 46 % and 0.1 % nBPT as urease inhibitor (urea+UI).

6.3.4 Experimental design

Table 1: 2-Factorial Design of treatments in the 1st (Determination of mineralization) and 2nd (Determination of gaseous flux) experiment. Wheat residues (ws) were incorporated into the soil, fertilizer granules were applied to the surface of individual repetitions.

Treatment	Residues	Fertilizer
- ws -N	No	No
- ws + urea	No	Urea
- ws + urea+UI	No	Urea + Urease Inhibitor nBPT
+ ws -N	Yes	No
+ ws + urea	Yes	Urea
+ ws + urea+UI	Yes	Urea + Urease Inhibitor nBPT

The two experiments of the research described in this report were designed as 2-factorial experiments (table 1) and were carried out under the same conditions in order to ensure the comparability of the results. The amount of wheat straw homogeneously mixed into the soil was calculated to reflect the addition of 5 Mg (straw) ha⁻¹ in a farmer's field,

corresponding to 1.92 g (wheat straw) kg (soil)⁻¹. For the fertilized treatments, granules of Urea or Urea + UI (UTECH) were applied to the soil surface in the incubation glasses. The addition of N was calculated to reflect the application of 250 kg (N) ha⁻¹. For the determination of N turnover, the calculation was based on soil weight (40 mg (Urea) 75 g (soil)⁻¹); for the determination of gaseous flux, the application of urea was based on the surface area of incubated soil (250 mg (urea) 200 g (soil)⁻¹) (table 1). Both experiments included 5 repetitions of each treatment to allow appropriate statistical analysis of the results.

6.3.5 First Experiment (determination of N turnover)

Treatments for the determination of N turnover were prepared as described above. For each treatment, repetition and sampling date, an individual screw-top glass was filled with 75 g soil and brought to a soil water-content of 20 % (optimal, judged on experience) using distilled H₂O. Each glass was closed using plastic paraffin film to avoid evaporation while allowing gaseous exchange. Soil was incubated in a climate chamber at 18 °C for 19 days.

Sampling occurred on days 0, 1, 3, 7, 11 and 19. For the extraction of mineral N from soil, 200 ml 0.5M K₂SO₄ were added to each screw-top glass and shaken at 180 rpm for 60 minutes. The concentrations of NH₄-

N and NO₃-N of the extract were analyzed through micro-flow auto analysis (SEAL QuAAtro). Results were calculated as mg (NH₄-N/NO₃-N) kg (soil)⁻¹. Apparent net N mineralization was calculated.

6.3.6 Second Experiment (determination of gaseous flux)

To investigate the effects of nBPT and the addition of plant residues on the flux of CO₂, N₂O and NH₃, soil was incubated in a climate chamber at 18 °C for a period of 16 days. Incubation bottles were closed with silicone plugs provided with an air-inlet and outlet. Compressed air was passed over the samples at a rate of 13 ml min⁻¹. The air passed through a glass vial for the determination of CO₂ and N₂O flux rates, and finally through an acid trap containing 200 ml of 0.2M H₂SO₄, for the determination of total NH₃ emitted from samples. Sampling occurred on days 2, 4, 6, 8, 10, 12, 14 and 16. For each repetition of the treatments, 200 g soil, without or with wheat residues as described in table 1, were brought to a soil water-content of 20 % (optimal, judged on experience) using H₂O dest. and filled into the incubation bottles. For the fertilized treatments, granules of Urea or UTEC were applied to the surface of the soil before the individual glasses were attached to the air-flow system. At sampling, the glass vials were removed, and their content was analyzed for CO₂ and N₂O using gas chromatography (5890 series II,

Hewlett Packard) with an electron capture detector (ECD), the ammonia concentration in the acid-traps was analyzed through micro-flow analysis (SEAL QuAAtro).

Gas fluxes of CO₂ and N₂O were calculated according to the following equation:

$$gasflux_{CO_2, N_2O} = \frac{k_{CO_2, N_2O} ([CO_2, N_2O]_{IN} - [CO_2, N_2O]_{OUT}) s}{A} \quad (1)$$

where *gas flux* is the emission of CO₂ and N₂O in µg (CO₂-C, N₂O-N) m⁻¹ h⁻¹, *k* is the conversion constant for the mass conversion of CO₂-C, N₂O-N, [CO₂,N₂O]_{IN} and [CO₂,N₂O]_{OUT} are the concentrations of CO₂-C and N₂O-N before and after passing over the samples, respectively, *s* is the air flow rate of the system, and *A* is the inner diameter (surface area) of the incubation bottles.

NH₃-N was calculated as the total amount of NH₃-N emitted from the treatments at point of sampling.

6.3.7 Statistical analysis

The experimental results were analyzed applying the R environment for statistical computing (R Development Core Team, 2011), using a linear, 2-factorial analysis of variance (ANOVA) for each individual sampling

date. Differences between treatments were calculated using Tukey's test for Honestly Significant Difference (Tukey-HSD) at a confidence interval of $\alpha=0.05$.

6.4 Results

6.4.1 1st Experiment (determination of N turnover)

Fertilizer Effect

There was a significant effect of added fertilizer (urea and urea+UI) on measured concentrations of ammonium-N and nitrate-N in soil (figure 1). For ammonium-N, this effect was evident up to the 11th day of the experiment after which no significant differences between treatments were observed.

Comparisons between the two fertilizers showed significantly higher concentrations of ammonium-N in the urea treatment compared to urea+UI only for the first 7 days of the experiment, showing that UI reduces the appearance of ammonium-N, proving the inhibition of the urease enzyme.

Nitrate-N concentrations of both urea and urea+UI increased over the entire experimental period. The nitrate-N concentrations of the urea treatment were higher compared to urea+UI up to the final day of

sampling, at which no significant differences between the two fertilizer treatments were determined.

Disregarding the main effect of added wheat straw, the concentration of mineral N at the conclusion of the experiment was 104.4 and 107.1 mg (N) kg (soil)⁻¹ for urea and urea+UI, respectively (table 2).

Table 2: Apparently net mineralized N (NH₄-N + NO₃-N), total CO₂-C respiration, total N₂O-N emission and total NH₃-N volatilization at the conclusion of the experiments (2 weeks), showing the main effects of the 2-factorial experimental design (wheat straw x fertilizer) in the two experiments (Exp. 1 and Exp. 2).

Treatment	Residues	Fertilizer	net mg (N) kg ⁻¹ ± SE	CO ₂ -C g m ⁻² ± SE	N ₂ O-N mg m ⁻² ± SE	NH ₃ -N g m ⁻² ± SE
- ws -N	No	No	29.6 ± 0.1	3.9 ± 0.3	3.4 ± 0.4 c	0.0 ± 0.0
- ws + urea	No	Urea	170.3 ± 4.7	24.0 ± 1.0	84.6 ± 5.0b	2.9 ± 0.4
- ws + urea+UI	No	Urea + UI	167.7 ± 5.1	12.4 ± 3.9	14.3 ± 4.1 c	0.1 ± 0.1
+ ws -N	Yes	No	- 1.2 ± 1.0	33.2 ± 4.6	5.8 ± 0.4 c	0.0 ± 0.0
+ ws + urea	Yes	Urea	112.9 ± 4.5	56.9 ± 3.9	432.8 ± 33.0 a	3.5 ± 0.3
+ ws + urea+UI	Yes	Urea + UI	115.9 ± 9.0	48.6 ± 1.5	29.7 ± 2.0 bc	0.0 ± 0.0
Wheat straw (A)	No		122.5 ± 17.7 a	13.4 ± 2.5 b	34.1 ± 9.8 b	1.0 ± 0.4
	Yes		75.9 ± 14.9 b	46.2 ± 3.2 a	156.1 ± 53.3 a	1.2 ± 0.4
			***	***	***	n.s
Fertilizer (B)		No	14.2 ± 5.2 b	18.5 ± 5.4 c	4.6 ± 0.5 c	0.0 ± 0.0 b
		Urea	141.6 ± 10.0 a	40.4 ± 5.8 a	258.7 ± 60.1 a	3.2 ± 0.3 a
		Urea + UI	141.8 ± 9.9 a	30.5 ± 6.4 b	22.0 ± 3.4 b	0.1 ± 0.0 b
			***	***	***	***
A x B			n.s	n.s	***	n.s

Tukey HSD: Signif. Codes: 0 '**' 0.001 '***' 0.01 '**' 0.05 '.' no difference 'n.s'**

Δ mineral N: (NH₄-N + NO₃-N)_{End} - (NH₄-N + NO₃-N)_{Start}

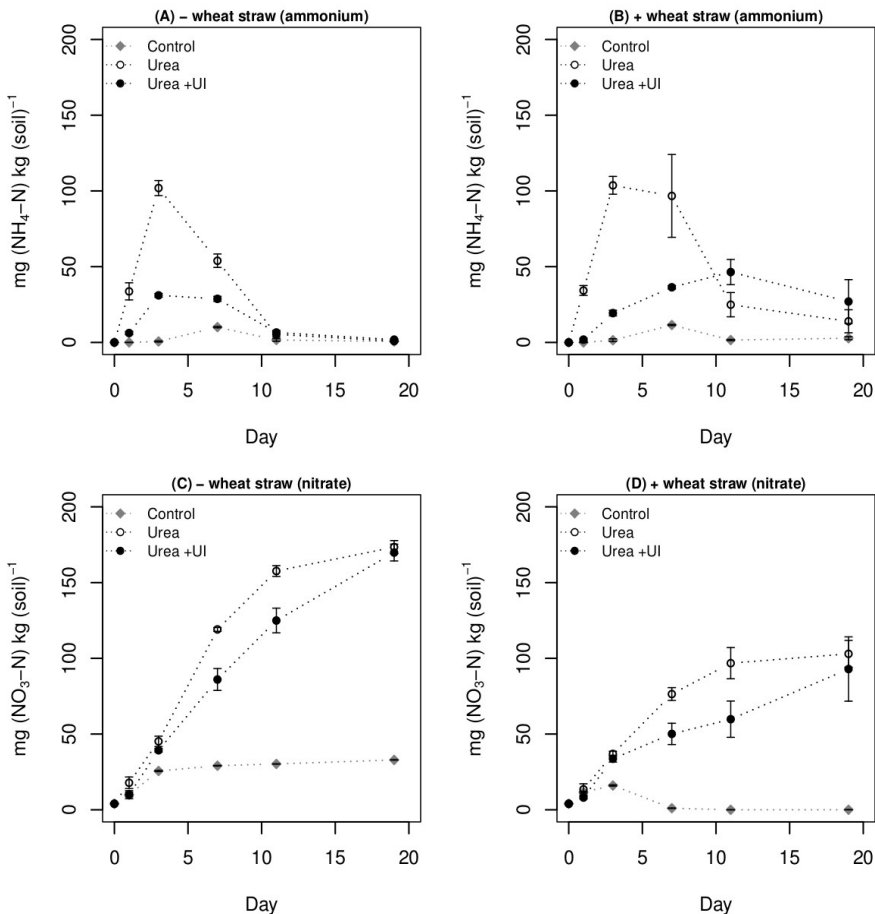


Figure 1: Turnover of ammonium-N and nitrate-N in alkaline soil of the NCP after application of Urea and Urea + UI (nBPT) without (left) and with (right) incorporated wheat straw. Error bars indicate the standard error of the mean.

Nitrate-N concentrations of both urea and urea+UI increased over the entire experimental period. The nitrate-N concentrations of the urea

treatment were higher compared to urea+UI up to the final day of sampling, at which no significant differences between the two fertilizer treatments were determined.

Disregarding the main effect of added wheat straw, the concentration of mineral N at the conclusion of the experiment was 104.4 and 107.1 mg (N) kg (soil)⁻¹ for urea and urea+UI, respectively (table 2).

Effect of added wheat straw

The incorporation of wheat straw showed a trend towards higher ammonium-N concentrations in the second week of the experiment both after the addition of urea and urea+UI (figure 1 A + B), with a significant main effect on the concentrations of ammonium N on the final two days of the experiment (days 11 and 19). In contrast, the addition of wheat straw led to a 35% lower concentration of nitrate-N, compared to soil without added wheat straw (figure 1 C + D).

Peak concentrations of ammonium-N and nitrate-N

Urea as N-source led to peak concentrations of ammonium-N on the third day of the experiment (-wheat straw: 76 mg (N) kg (soil)⁻¹; +wheat straw: 77 mg (N) kg (soil)⁻¹). For urea+UI, peak concentrations of ammonium-N were observed on day three (-wheat straw: 23 mg kg (soil)⁻¹) and day 11 (+wheat straw: 35 mg kg (soil)⁻¹). These days must be regarded as the point in time where the rate of nitrification exceeded

the rate of urea-hydrolysis (figure 1).

Nitrate-N concentrations continuously increased up to the final day of sampling. The observed values of mineral N (ammonium-N + nitrate-N) at the conclusion of the experiment are approximately 50% of added fertilizer-N (table 2).

6.4.2 2nd Experiment (determination of gaseous flux)

CO₂ respiration

The addition of wheat straw led to a significant increase in CO₂ respiration as compared to the treatments without added wheat straw over the entire course of the experiment. For the treatments without added wheat straw, CO₂ respiration rates of the fertilized treatments increased throughout the experiment, leading to peak CO₂ respiration rates of 105 mg (CO₂-C) m⁻² h⁻¹ (urea) and 54 mg (CO₂-C) m⁻² h⁻¹ (urea+UI) on day 16. For the treatments with added wheat straw, peak CO₂ respiration was observed on day 3 of the experiment with 180 and 170 mg (CO₂-C) m⁻² h⁻¹ for urea and urea+UI, respectively.

The control in both instances showed similar CO₂ dynamics compared to the fertilized treatments, at lower concentrations (figure 2 A + B).

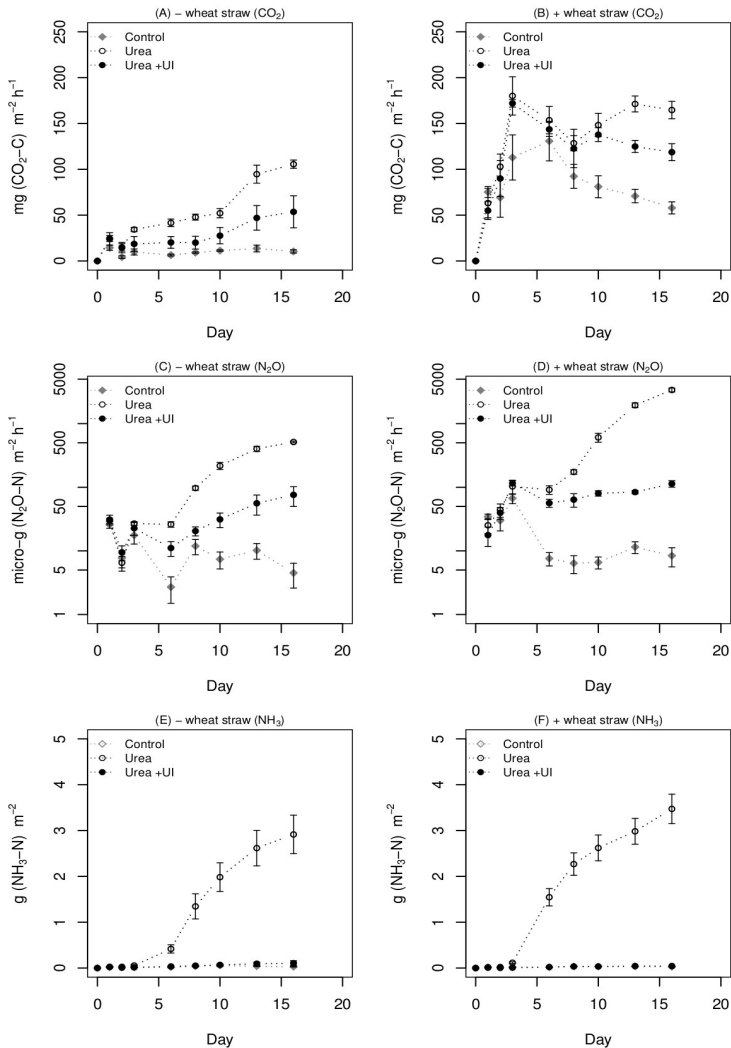


Figure 2: Flux rates of $\text{CO}_2\text{-C}$, $\text{N}_2\text{O-N}$ (logarithmic scale) and total loss of $\text{NH}_3\text{-N}$ from alkaline soil of the NCP after application of Urea and Urea + UI (nBPT) without (left) and with (right) incorporated wheat straw. Error bars indicate the standard error of the mean.

With regard only to the main effect of added wheat straw, total CO₂ respiration increased from a mean of 13.4 to 46.2 g CO₂-C m⁻² over the experimental period. Further, there was a significant effect of added fertilizer on CO₂ respiration (Control < urea+UI < urea, table 2), in excess of the possible 5.8 g CO₂-C m⁻² that theoretically may be released from urea at the chosen application rates. There was no significant interaction between the main factors of the experiment (wheat straw x fertilizer).

N₂O emission

The incorporation of wheat straw increased the emission of N₂O in soil treated with urea and urea+UI. The observed effect of both fertilizers was evident from the 3rd day of sampling and remained elevated compared to the control throughout the experiment. In the 2nd week of sampling, a significant interaction between the main effect of added wheat straw and fertilizer became evident. This interaction was evident only for the treatments fertilized with urea, not urea+UI.

In all treatments, the highest N₂O emission rates were observed on the final day of sampling and flux rates increased with the addition of wheat straw. With urea as fertilizer, N₂O flux rates were 515 and 3390 µg N₂O-N m⁻² h⁻¹, with urea+UI flux rates were 76 and 113 µg N₂O-N m⁻² h⁻¹ without and with added wheat straw, respectively (figure 2 C + D).

There was a significant interaction effect between the factors of wheat

straw and fertilizer on the emission of N_2O , which is reflected in the calculated total emission of N_2O over the duration of the experiment. For soil fertilized with urea, the total emission of N_2O at 432.8 mg m^{-2} with added wheat straw was 5 times higher compared to soil without added wheat straw at 84.6 mg m^{-2} . In contrast, N_2O emission from soil fertilized with urea+UI remained at a low level, with total values of 14.3 mg m^{-2} without added wheat straw and 29.7 mg m^{-2} with added wheat straw (table 2).

NH_3 volatilization

There was a response of ammonia volatilization only from treatments fertilized with urea. For both the control and urea+UI, only trace amounts of ammonia were determined in the sulfuric acid traps used in this experiment.

Peak volatilization rates of ammonia from soil fertilized with urea were observed on the 8th day of the experiment for soil without added wheat straw ($19.3 \text{ mg NH}_3\text{-N m}^{-2} \text{ h}^{-1}$) and on the 6th day for soil with added residues ($19.2 \text{ mg NH}_3\text{-N m}^{-2} \text{ h}^{-1}$), after which volatilization rates decreased until the conclusion of the experiment (figure 2 E + F).

Total volatilization of ammonia over the experimental period from soil fertilized with urea amounted to 2.9 and 3.5 g m^{-2} for soil without and with added wheat straw, which corresponds to a loss of 12 and 14% of applied urea, respectively (table 2).

6.5 Discussion

For soil without added fertilizer, the N dynamics in soil used for these experiments are consistent with previous research on the subject (*Gioacchini et al.*, 2006; *Mary et al.*, 1996). The non-amended soil showed a total apparent of about 21 mg (N) kg (soil)⁻¹ over a 3 week period, which translates to about 20 kg (N) ha⁻¹ taking a depth of 10cm as a basis for calculation. In contrast, soil amended with wheat straw led to a net-immobilization of 2 mg (N) kg (soil)⁻¹. Similar results have been described by *Mundra et al.* (1973), *Nieder and Richter* (1989) and *Mary et al.* (1996), who state that net immobilization takes place on a short-term when organic material with a C:N ratio wider than 25:1 is incorporated to soil.

As expected, the addition of wheat straw led to an increase in CO₂ respiration, i.e. microbial activity, over the first week of the experiment, before gradually declining in the second week of the experiment. Similarly, without additional N, N₂O flux rates were elevated only for the first few days of observation, before decreasing to levels similar to those observed in pure soil. These observations may indicate that microbial activity was limited by N as a substrate for microbial activity, as described by *Zumft et al.* (1997).

Soil treated with urea

The observations on the turnover of urea, especially the concentrations of ammonium-N, indicate that the hydrolysis of urea as catalyzed by the urease enzyme reaches its maximum within 3 days after application, and that nitrification is induced quickly. These dynamics of N are expected after urea application, and are consistent with previous research on the subject (Marsh et al., 2005).

The addition of wheat straw in this experiment led to a prolonged presence of ammonium-N in soil and to reduced concentrations of nitrate-N over the course of the experiment. It is therefore possible that the addition of wheat straw either stimulates the activity of the urease-enzyme, or reduces the rate of nitrification, thereby acting as a nitrification inhibitor. This specific result in part contradicts observations by Marsh et al. (2005), who state that nitrification after urea application is induced quickly in a wide range of conditions, as urea acts both as a C and N source for ammonia oxidizing bacteria. With regards to total mineral-N, the addition of wheat straw led to lower total concentrations of N, which may be explained through an increase in the microbial-N fraction (Mary et al., 1996) during the decomposition of organic material (Nieder and Richter, 1989).

As has been previously reported, the application of urea to alkaline soils may lead to a significant loss of N in the form of ammonia (McKinnes et al., 1986; Sommer and Jensen, 1994; Zhang et al., 2011). In these

experiments, the loss of N through ammonia volatilization after the application of urea amounted to 2.9 g (NH₃-N) m⁻² without added wheat straw, and 3.5 g (NH₃-N) m⁻² with added wheat straw, which is 12 and 14% of applied urea-N, respectively. These rates of volatilization are lower compared to research conducted by McKinnes et al. (1986), Zhang et al. (2011) and Rodriguez Soarez et al. (2012), but are similar to the results obtained by Sanz-Cobena et al. (2008).

The addition of urea significantly increased respiration rates of CO₂ compared to the unfertilized treatments without and with added wheat straw. Taking the application rate of urea as a basis for calculation, only 5 g (CO₂-C) m⁻² can be explained from the hydrolysis of urea; CO₂-emission above these values must be explained through background soil respiration (no added wheat straw) or the turnover of added organic material (wheat straw). These values indicate that there is a priming effect of urea on the activity of microbial organisms, and thereby CO₂-respiration, as described by Kuzyakov et al. (2000). In this case, urea would act as both an N and C source for microbial organisms, leading to an increase in soil activity and the turnover of added organic material.

A similar priming effect must also be responsible for the increase in N₂O flux rates observed in this experiment. The addition of urea increased emission rates of N₂O-N by a factor of 10 compared to soil without added fertilizer and without added wheat straw, and by a factor of 100 compared to soil without added fertilizer when wheat straw was

incorporated. Generally, N₂O emission is limited either by the absence of N as a substrate (Zebarth et al., 2008), or by C as a limiting factor of microbial activity (Pfab et al., 2012). In the case of the research presented here, the addition of urea may act both as a C and N source (Marsh et al., 2005), causing a priming effect on microbial activity, thereby leading to the interaction effect of added urea and wheat straw on N₂O emission.

Unfortunately, the design of this study cannot show the contributions of nitrification and denitrification processes to N₂O emissions. At the soil moisture levels chosen for these experiments, it is possible that the processes of nitrification significantly contribute to the loss of N₂O as described by Baggs (2008) and Kool et al. (2011).

Soil fertilized with urea + UI

Three principal points must be made when comparing urea+UI to urea. Firstly, the use of UI does effectively limit the rate of hydrolysis as catalyzed through the urease enzyme. Yet, while the appearance of ammonium-N is reduced in incubated soil and the subsequent appearance of nitrate-N is slightly reduced, the activity of the urease enzyme seems sufficient to provide ammonium-N as a substrate for nitrification.

Secondly, UI almost completely prevented the loss of N as ammonia in these experiments. The volatilization of NH₃-N was undiscernibly

higher compared to the unfertilized control over a period of 2 weeks. While the efficiency of nBPT concerning the volatilization of ammonia has previously been described (Watson et al., 1990; Gioacchini et al., 2002; Kawakami et al., 2012; Rodrigues Soares et al., 2012), this near complete restriction of ammonia volatilization is surprising, and should be confirmed using more sensitive methods of analysis.

Finally, UI strongly reduced the loss of N as N_2O after application of urea, which supports the suggestion of Ding et al. (2011), who described that the loss of N_2O may be reduced by the urease inhibitor nBPT. Unfortunately, as the emission of N_2 could not be measured in this experiment, it is not possible to conclude whether gaseous N loss is entirely prevented, for instance, through an inhibition of denitrification processes or through the rapid oxidization of nitrite as a substrate of N_2O loss from nitrification, or whether a shift towards the loss of N as N_2 during the process of denitrification occurred.

In addition to the results on NH_3 -volatilization and N_2O -emission, the results further show that CO_2 -respiration is reduced through UI. In the context of N_2O -emission, this result specifically may lead to either of two conclusions: UI may either simply act restricting on microbial activity in general, or the principal mechanisms of the urease inhibitor may prevent the priming effect of urea on soil microbial activity, as the C fraction of urea is not available as a substrate for microbial growth (Kuzyakov, 2000; Marsh et al., 2005). Further research on the subject,

specifically on the effect of the urease inhibitor nBPT on the C and N turnover in soils is therefore necessary and should use marker-based studies to observe the development of mineral and organic C and N fractions in soils.

6.6 Conclusion

Despite the narrowness of the experimental design, this research allowed observations that warrant further investigations on the subject.

The urease inhibitor nBPT reduces the hydrolysis of urea, but not so strongly as to prevent or significantly delay the rate of nitrification, thereby the potential for N loss in the form of ammonia is reduced, while the availability of N for plants is maintained.

The addition of wheat straw prolonged the appearance of ammonia, leading to the question whether wheat straw in itself may act as a stimulant for the hydrolysis of urea, or as an inhibitor of nitrification.

Urea, as a C and N source, may have a strong priming effect on the activity of microbial organisms, thereby increasing soil respiration and increasing the risk of N loss in the form of N₂O. In contrast, these effects could not be observed for nBPT-amended urea.

Further research on the subject of urease inhibitors should include observations on the effect of the urease inhibitor not only on the

turnover of nitrogen, but also on the turnover of carbon, and the change in microbial processes following the application of urease inhibitors.

6.7 References

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7.1 Evaluation of N rates according to yield development and N cycling*Control*

The research presented here shows that the omission of N application in a previously over-fertilized field of the NCP did not immediately lead to a reduction in grain yield of summer-maize. The yield of the summer-crop was maintained for a period of up to two years before a yield depression was observed. In contrast, yield depression of wheat was immediately evident when no N was applied as fertilizer (chapter 2).

This yield development of the control treatment is essential in understanding N dynamics in a previously over-fertilized farmer's field of the NCP. The mineralization of N appears to begin in late spring, while the highest activity in mineralization takes place during the summer-vegetation period of maize (chapter 3). During the winter vegetation period of wheat, biological activity is strongly reduced due to cold temperatures and dry soil conditions. As a consequence, N accumulated in the crop residues of maize may only be available to the following summer-crop, while the winter crop is dependent on the application of N fertilizers in order to maintain the yield level.

Although these results were not entirely expected, they give an

indication on when the application of N is necessary and when the application of N must be reduced in order to prevent N loss.

The fertilization of N at the seeding of wheat is unnecessary for yield development. An application of N in spring, at the regreening of wheat, is essential for yield development of the winter-crop. The application of N for the summer-crop (maize) may be strongly reduced, as the mineralization potential in the soil of a previously over-fertilized field will meet the N demand of the crop after seeding. Further applications of N during this period of time are subjected to the previously described loss pathways.

Current Farmers' Practice

As previously discussed (chapters 2 and 3), the current application rate of $550 \text{ kg N ha}^{-1} \text{ a}^{-1}$ according to farmers' practice has no benefits regarding the yield of a wheat / maize double-cropping system compared to reduced application rates based on crop demand and the N_{\min} status of the soil.

The negative effects of the over-application of N in the form of urea are evident, though. It has been well described that the potential loss of N increases when the surplus after harvest lies above a threshold value of about 50 kg N ha^{-1} (Subbarao et al., 2006).

For the specific case of over-application of N in the NCP, the main processes of N loss are the leaching of nitrate and the gaseous loss of N

in the form of ammonia and NO_x . Although the environmental impact of nitrate leaching in this particular area of the NCP is debatable due to the significant depth of soils, the leaching of N is wasting a valuable resource. The main events of N leaching most likely occur during flood irrigation and during the summer vegetation period, where intensive precipitation (figure 1.1) causes a downward movement of water through the soil profile.

The gaseous loss of N, with its impact on environmental change and human health is of higher importance for China, though. Especially urea as an N source has a high potential for N loss in the form of ammonia after application and as a driver of N loss through N_2O emission (chapter 6).

A further problem lies in the specific weather pattern of the NCP. The onset of winter leads to a sharp decrease in temperatures and rainfall after the sowing of wheat and soil activity remains low until the following spring. The mineralization of organic residues is likely to occur mainly during the summer vegetation period. Therefore, N contained in the plant material of maize apparently “carries over” to the following summer vegetation period, when there is an increased risk of N loss. In the case of N application according to FP, this “carry over” effect poses a significant contribution to the over-supply of N and the associated loss of N to the environment.

Fertilization according to farmers' practice is therefore untenable and it

is of absolute necessity to reduce N application rates, especially over the summer vegetation period, in order to reduce the intense cycling of N and reducing N loss to the environment.

N application according to crop demand and N_{min}

Adjusting N application rates for the wheat/maize double cropping system by calculating crop N demand and the N_{min} status of the soil is a valid tool for reducing N application rates. The adaptation of N application rates has no observable negative effect on yield formation. A reduction by at least 40 % compared to farmers' practice is possible, without negatively affecting the yield of the double-cropping system (chapter 2). These results are in accordance with previous research that has been carried out in the NCP (Chen, 2003; Cui et al., 2006; Meng et al., 2012).

However, the reduction of N application rates did not immediately, or at least only partly, lead to an increase in N use efficiency (chapter 2). As was previously discussed, the mineralization of N plays a significant role in crop N supply, especially over the summer vegetation period and must be taken into account should N application be further reduced and NUE increased.

In spite of this drawback, the benefits of calculating N rates according to crop demand and the N_{min} status of the soil are evident. The N surplus after the harvest of crops is reduced compared to FP, which improves

residual N_{\min} in the soil and the cycling of N within the system (chapter 3).

Unfortunately, it is unlikely that this system for the calculation of N application rates can be applied to the NCP at this point of time. The main restriction in implementing this measure is the system of small-scale agriculture that dominates the NCP and prevents the necessary wide-spread soil analysis.

An alternative to the system of N_{\min} based crop N recommendations may be the use of regionalized crop-growth models calibrated to the conditions of the NCP, that calculate the N_{\min} status of the soil (chapters 4 and 5).

Simple recommendation based on crop N demand

As a short-term alternative to an N_{\min} based system of calculating N application rates, it is necessary to give a simple fertilizer recommendation that is based on N demand of the cropping system. The preliminary modelling results presented here (chapter 5) indicate that an approach based on crop N demand at an expected yield level would secure the yield of the double-cropping system, while greatly reducing N loss.

Such an approach has both drawbacks and benefits. Fertilization according to crop demand does not take the mineralization potential of soils into account. Therefore, the risk of over-application of N is higher

compared to an N_{\min} -based approach.

The benefit of such a recommendation, on the other hand, is that it is easy to understand and follow, and is therefore more likely to be applied by small-scale farmers in the NCP. Using such a system, the application rates of N would be immediately reduced compared to farmers' practice, but would provide sufficient N for the yield expectancy of the system. The intense cycling of N within the system, as previously described (chapters 2 and 3), would ensure that seasonal variability is compensated, possibly retaining excessive N in the system when yields are low, while releasing enough N through mineralization when yields develop better.

Taking an approach based on crop N demand, without regards to the N_{\min} status of the soil, is a compromise. Yet, the benefits of applying such a system by far outweigh the drawbacks, especially when the alternative is a continuation of current farmers' practice.

7.2 Strategies for reducing N loss

Apart from reducing N application rates, which in itself would reduce the potential for N loss, further tools for reducing the environmental impact of N fertilizer application exist and should, where possible, be implemented.

Sub-surface banded N application

The sub-surface application of ammonium-based N fertilizers such as urea, is an appropriate method for reducing N loss. It has been described that the potential of gaseous N loss is reduced when fertilizers are placed below the soil surface and that the leaching of nitrate is potentially reduced (Subbarao et al. 2006). The basic idea behind the method is that nitrification is inhibited through toxic concentrations of ammonium within the depot and that N is retained in the less mobile form of ammonium. As was shown, this method of N application may lead to a higher fertilizer efficiency of N when compared to the broadcast application of urea (chapter 2).

The sub-surface application of N fertilizers can be achieved using modified seeding machines that are widely available in the NCP and are well suited to the dominant small-scale farming operations.

While the use of liquid fertilizers, such as UAN solution, is difficult and not common in the NCP, urea is a suitable product for this type of N application. Apart from the positive effects of this method, the mechanical sub-surface application of N may further lead to a more uniform application of N in comparison to manual top-dressing and be less time consuming, thereby reducing the effort for farmers.

Stabilized fertilizers

DMPP: Similar to the concentrated application of ammonium-based fertilizers, the use of NI aims to stabilize N fertilizers in soils after application. The NI DMPP, that was used in the presented studies as ASN_{DMPP} inhibits the first step of nitrification through *nitrosomonas* bacteria. Previous research has shown that N use efficiency is increased through the addition of DMPP, especially on sites that are prone to the leaching of nitrate. These characteristics may therefore enable the use of lower application rates of N while reducing the need for frequent N applications (Zerulla et al., 2001).



Picture 1: Modified seeding application attached to a small tractor typical for the NCP. These applications and tractors are widely used by local farmers.



Picture 2: Sub-surface application of urea between the rows of winter-wheat at the stage of re-greening in March.

In comparison to urea, as well as UAN solution, ASN_{DMPP} showed the most favorable results with regards to yield formation of wheat and maize, as well as agronomic N efficiency (chapter 2) even though no significant benefits in comparison to urea could be determined in terms of soil N dynamics (chapter 3). The yield increase in comparison to both FP and the reduced application of urea (chapter 2) is comparable to previous research carried out by Pasda et al. (2001), who observed a yield increase of 0.25 Mg ha^{-1} when DMPP was added.

Products such as ASN_{DMPP} require no special equipment in comparison to placed N application and could easily be applied by farmers in the NCP. The main criteria restricting the use of such a fertilizer is the high cost in comparison to urea. For small-scale farmers in the NCP it is

unlikely that there will be a financial benefit, unless the government-subsidies for urea are stopped.

NBPT: As an N source, urea is predominant in the NCP and is unlikely to be replaced soon, due to competitive pricing and high availability in China. The main disadvantage of urea lies in the high potential of NH_3 volatilization after application and also in its potential as a driver of soil microbial activity, increased respiration and gaseous losses of N (chapter 6). Kuzyakov et al. (2000) stated that urea may act as both a C and N source for soil microbes, priming soil activity and leading to increased emissions of N_2O . While NI have been shown to effectively reduce the loss of N_2O throughout the vegetation period (Pfab et al., 2012), it is possible that NH_3 volatilization is increased when N is retained as ammonium on soils with a high pH. Therefore, it is attractive to inhibit the upstream step of urea hydrolysis in order to reduce the loss of N through volatilization and nitrification/denitrification processes.

nBPT, which inhibits the *urease* enzyme, has been shown to effectively reduce the loss of NH_3 , thereby increasing N use efficiency on a variety of crops (Watson et al., 1990; Kawakami et al., 2012, Rodrigues Soares et al., 2012). In addition to this primary effect, it is possible that nBPT may reduce the priming effect of urea on microbial activity, thereby reducing the loss of N through N_2O emission.

While the activity of the *urease* enzyme is restricted, the results of this

research indicate that the rate of hydrolysis may sufficiently supply ammonium as a substrate for nitrification, thereby ensuring the availability of N for plant consumption (chapter 6).

As urea-based products would be less expensive, the chance of introducing nBPT-stabilized urea on the Chinese market is higher compared to ASN_{DMPP} .

7.3 Prerequisites for improving N management in China

Galloway et al. (2008), Lhada et al. (2005) and Subbarao et al. (2006) have all summarized the risks of over-application of N on a global scale and have highlighted steps that must be taken towards reducing the environmental impact of fertilizer consumption. Ju et al. (2009) addressed the challenges of intensive Chinese agriculture in particular, stating that the improvement of extension services and the education of farmers concerning fertilization is detrimental to improving N management in the NCP.

The main prerequisite for the reduction of N consumption in Chinese agriculture is, indeed, the education of farmers, where basic principles of agriculture and the environmental impact of agricultural practices are concerned. Such education could be achieved by the cooperation of government controlled extension services, scientific research and the

local and national media.

The extension services in rural areas in China must be improved with regards to the distribution of extension offices in order to cover the main agricultural production areas (Ju et al., 2009)

Research suggests (Huang et al., 1999) and practical observations in the NCP confirm, that the agricultural extension services are not complying with their intended function. Weber and Bergmann (2011) indicated that the decision making process of farmers is influenced more by their social circles (关系 *guānxi*) than by the recommendations of the extension services. In order to reverse this situation, it is necessary to establish a functioning agricultural extension service that is able to transfer scientific findings and developments to small-scale farmers.

The scientific community must communicate its findings both to the agricultural extension services and the rural population and include integrated approaches to their research. A recent program carried out by the China Agricultural University involves placing students in rural villages in order to implement and discuss methods for improving agricultural practices. By involving local extension services into programs such as these, information on best agricultural practices could be spread more effectively.

The implementation of these programs should be accompanied by analysis of the “diffusion of innovations” (Rogers, 1982) in order to identify the processes through which innovative, sustainable agricultural

management practices are accepted and to identify the reasons for the success or failure of these practices.

In order to transfer these findings to the public, it might be necessary to involve local and national media, including newspapers and television as well as the internet. These resources may play a valuable role in communicating the relationship between fertilization practices and environmental impact to rural communities.

7.4 Strategies for improving N management

There is no single, straightforward solution to the problems of over-fertilization in the NCP and the negative effects associated with the excessive application of chemical N. Strategies for improving agronomic measures in the NCP must rather be separated into immediate (short-term), intermediate (mid-term) and long-term steps towards improved fertilization practices and mitigation of N loss pathways.

The immediate strategy for N management in the NCP must be a drastic decrease in N application rates. This is only possible by informing small-scale farmers on the relationship between over-fertilization and negative environmental effects that are already evident in China.

As it is currently unlikely that measures for the determination of soil N

concentrations can be implemented, the goal in this first step must be to adjust N application rates to the N requirement of cultivated crops. The surplus of N application, meaning the difference between N applied to the field and N removed in plant material, should not exceed 50 kg N ha⁻¹, which has been accepted as the value at which N is increasingly subjected to N loss pathways (Lhada et al., 2005; Subbarao et al., 2006). For the double-cropping system of Quzhou county, with an expected yield of 6-8 t wheat and 8-10 t maize, the rate of N would require the application of 30 kg (N) ha⁻¹ in the form of an N-P-K compound fertilizer at the sowing of wheat and 150 kg (N) ha⁻¹ in the form of urea at the regreening of wheat. During the summer-vegetation period, 30 kg (N) ha⁻¹ should be applied as N-P-K fertilizer at the sowing of maize, followed by the application of 90 kg N ha⁻¹ as urea at 4-6 leaf stage. According to this recommendation of 300 kg (N) ha⁻¹ a⁻¹, the N input could immediately be reduced by 45% compared to current farmers' practice.

The distinct characteristics of the region, with regards to soil activity and mineralization as well as the rainfall pattern, allow an emphasis on N application for wheat, which is more dependent on the application of N for yield formation, while N application during the maize vegetation period should be more restrained, as the potential for loss is higher during the summer vegetation period (chapters 2 and 3).

The research presented here, as well as previous research on the subject,

indicates that the adjustment of N application rates will not negatively affect the yield level of wheat and maize in the NCP. Rather, a large portion of reactive N, which is currently a substrate for N loss pathways will be removed from the equation and will further reduce the impact caused by the production and transport of chemical N sources (Zhang et al., 2013). Even though the financial incentive for farmers may be negligible, as urea as an N source remains cheap, the possibility of avoiding over-expenses and labor time associated with the application of fertilizer should not be dismissed.

There are no real drawbacks to this first step, which has become not a demand to farmers, but an absolute necessity if the negative impact of agriculture on the environment is to be reduced.

The intermediate steps towards improving agricultural practice in the NCP involves the improvement of N application techniques, the encouragement of farm consolidation and the implementation of information systems that advise farmers on optimal N application rates.

Small-scale farmers in the NCP still resort to hand-dressing of fertilizer. Although practice may lead to a certain degree of proficiency in this technique, the use of specialized machinery for the spreading of fertilizer allows higher control of the application rate as well as a higher degree of accuracy in the spreading pattern. The development of machinery suited to the conditions of the NCP, i.e. small fields and small tractors that apply fertilizer in a sub-surface band as described

(chapter 2), could improve N application to agricultural fields. Although the optimal depth of fertilizer placement is debated, there is a consensus that the sub-surface application of N fertilizers is a viable technique for reducing both gaseous N loss as well as preventing the leaching of N (Cavigelli and Parkin, 2012; Eagle et al., 2011; Snyder et al., 2009).

Many of the proposed recommendations that aim for an increase in N use efficiency, namely the adjustment of N rates, best practice, the use of specialized machinery and agronomic measures as well as precision agriculture (Lhada et al., 2005, Subbarao et al., 2006; Galloway et al., 2008, Ju et al., 2009) demand a high degree of education as well as financial capital of farmers, which can only be achieved through a high degree of professionalism. This cannot be expected from small-scale farmers that rely on off-farm employment for their income.

A significant reduction of surplus N after harvest, a major contributor of the substrate for N loss pathways can only be achieved by taking the N_{\min} concentration and mineralization potential of soils into account (Wehrmann and Scharpf, 1997). Currently, the sheer number of individual farmers as well as the small size of fields prevents the effective implementation of legislature such as the European “Nitrate Directive” (1991), which in Germany is realized through the “Düngeverordnung” (DüV 2006). This directive calls for the implementation of best agricultural practice and the regular control of N application in order to restrict the loss of N to the environment. For the

NCP, an intermediate step could be achieved by adopting regionalized models (chapter 4) that estimate the processes determining the availability of N before fertilizer application, i.e. the yield level of the previous crop, N use and climatic conditions. The optimal N rates must be made available for field sizes based on multiples of the area dimension 1 mǔ (亩), which is $1/15$ of a hectare. The information produced by such a model, supervised by the scientific community, could then be communicated to farmers via the extension services and local media.

The consolidation of farms through the transfer of land use rights would create larger farms that may be managed more efficiently, thereby allowing for a higher income of farmers and encouraging the implementation of best agricultural practices. The incentive for reducing the input of agrochemicals would be higher as the potential of cost-reduction increases. Further, higher educated or experienced full-time farmers may act as innovators or early adopters of improved agricultural techniques, thereby influencing the practices of their immediate social circles (关系 guānxi) (Weber and Bergmann, 2011; Rogers, 1982).

In the long-term, the implementation of strategies necessary for a balanced N fertilization regime as suggested by Galloway et al. (2008), Lhada et al. (2005), Subbarao et al. (2006) and Ju et al. (2009) must be achieved.

The first of these long-term achievements must be the installment of a

functioning extension service that can communicate scientific findings and technical achievements to the farming community.

These extension services should also be involved in soil tests that monitor the N levels in fields and control the estimation of N balances on a field and regional scale. Such a system should at first involve larger, consolidated fields, in order to include data from these operations into the model recommendations for smaller, more traditionally sized fields.

The advances in plant breeding will eventually lead to more N efficient crops that reduce the surplus in agricultural fields after harvest. New, proven varieties must be distributed quickly, and N application rates may be adjusted to the demand of new crops.

Finally, it would be beneficial to take advantage of the advances in fertilizer technology. The use of fertilizers that inhibit nitrification or the activity of the urease enzyme should be encouraged to further reduce the loss of N. Here, the main restriction lies in the cost of these fertilizers in comparison to the widely available urea.

7.5 Scientific Outlook

The research presented here has generated some scientific questions that must be addressed in further studies:

1) The turnover of N in the wheat-maize double-cropping system of the NCP must be fully characterized in order to estimate the scope of mineralization within the cropping cycle. The indications of this research are that the re-supply of N during the summer-vegetation period may be sufficient for the summer-crop, maize. Should this assumption be confirmed, it would have detrimental implications in terms of crop response to N application, N loss pathways and the approach towards reducing N fertilization in intensive cropping systems of the NCP.

In order to fully characterize mineralization, ^{15}N marker-based studies are needed in order to observe the turnover of N. Three application rates of N should be included in such a study: an unfertilized control treatment; a farmers' practice treatment; a treatment fertilized according to crop requirement and N_{\min} .

Using ^{15}N marked fertilizers for the vegetation periods of maize and wheat, such an approach would allow an honest estimation of N use efficiency, as well as the extent and timing of N release to subsequent crops.

2) The research presented in this thesis indicates that N may indeed not be the limiting factor for plant growth. The soil conditions of the NCP, as well as current farmers' fertilization practices may lead to the assumption that other nutrients, mainly P, are limiting plant growth and

yield development in the region. As limited plant growth through nutrient deficiency has direct implications on N uptake of crops, it is necessary to investigate whether an optimization of P application may lead to an improved development of crops, as well as N and P use efficiency.

Investigations in this direction should, perhaps, use a 2-factorial experimental design. Observations on the effect of P fertilization (farmers' practice and optimized) on yield development and N use efficiency of different N treatments (farmers' practice and optimized) may lead to further insight on low N use efficiency in intensive Chinese cropping systems.

3) The use of crop-growth models for the estimation of N requirements shows enormous potential, especially for countries with prevalent small-scale agriculture, such as China. Further research should address how these models can be improved and used as a tool for giving agronomic advice in rural areas.

With regards to improving nutrient (N and P) efficiency in China, a crop-growth model calibrated for the conditions of the NCP, as described in this thesis, is a valuable tool for further research. The model should be used to make a preliminary assessment on the viability of different approaches towards improving nutrient use, thereby allowing focused research on the subject.

4) The investigations on the turnover of urea in soil from the NCP and on the effect of the urease inhibitor nBPT have led to important research questions that must be investigated in further experiments. The observation that urea may have a priming effect on microbial activity has important implications as urea, the most commonly used fertilizer in China, may not only be subjected to gaseous N loss but may be a significant driver of these processes.

In light of these findings, it is necessary to investigate the turnover of urea more closely and to identify factors affecting the loss of N after urea application. Further, a closer look at the functioning of the urease inhibitor nBPT is necessary and may be helpful in investigating the effect urea has on microbial activity.

The findings of this research, i.e. the effect of UI on the reduction of gaseous N loss, as well as the availability of N for plant growth, must be investigated in field trials in order to confirm the observations of this thesis.

8 Conclusion

With regards to the aims and objectives of this thesis, the presented results show that a reduction of N application rates according to crop demand and soil mineral N status is achievable in intensively cultivated farmers' fields. While the grain yield of a summer-maize / winter-wheat double-cropping system is not negatively affected, such a system for the calculation of N application rates reduces the over-application of N compared to current farmers' practice. Both the recovery efficiency as well as the agronomic efficiency of N are thereby increased.

The reduction of fertilizer N is possible even with a single application of N per crop. A continuous control of the soil N_{\min} status, as well as split applications of fertilizer, shows no advantages either for summer- maize or winter-wheat. This observation is encouraging as regular soil analysis is currently unachievable due to the structure of the agricultural system in the NCP. Further, an approach towards reducing N loss that generates a higher workload for small-scale farmers is undesirable and is unlikely to be accepted.

Further reductions in N application rates can only be achieved by developing a viable method for estimating the mineralization potential of soils. While it has previously been known that there is a significant resupply of N to subsequent crops in the NCP, the results of this research indicate that there is no definitive agronomic response of

summer-maize to N application for a period of up to two years. This development is an effect of the ongoing system of over-fertilization in the NCP. Further research is needed in order to clearly evaluate the rate of N supply through mineralization during the summer-vegetation period of double-cropping systems of the NCP in order to identify the extent to which N application for the summer-crop may and must be reduced.

Additionally, this research shows that the chemical stabilization of ammonium-based fertilizers, either through the use of DMPP or through the concentrated, sub-surface application of N, may increase yields and N use efficiency in the described agricultural system. ASN_{DMPP} , as used in this experiment, continuously achieved high yields and may be an alternative to the commonly used urea even though the higher cost of such products may limit acceptance. As an alternative, application techniques for the sub-surface application of urea should be pursued in order to minimize the risk of N loss through leaching or through gaseous loss of N after application.

In comparison to current farmers' practice, the N_{min} -based approach to the calculation of N application rates reduces N surpluses after harvest. In turn, the accumulation of N in the soil profile and the risk of N losses through leaching are reduced. The results of this thesis further show that the past, and still ongoing, practice of excessive fertilization leads to a strong accumulation of N in the biomass of maize and the rapid

mineralization of N during the summer months. While the risk of N loss is comparably low during the winter-vegetation period, research aiming to reduce N losses in the NCP must identify solutions to the loss of N during the summer-vegetation period, as the supply of N through mineralization in combination with fertilizer application leads to an extremely high risk of N loss in summer.

Based on these results and based on the agricultural structure of the NCP it is necessary to depart from the idea of basing N application on the demand of single crops. For this agricultural system it is rather necessary to take the N demand of the entire double-cropping cycle into account. The emphasis should lie on the supply of N to wheat, which is dependant on fertilizer N for yield formation. At the same time, the risk of N loss during the winter vegetation period is comparably low. The application of N to maize must be strongly reduced, as mineralization adds to N supply and the risk of N loss during the summer vegetation period is high.

The data from field experiments conducted in the NCP during the course of this research was successfully used to calibrate and validate a plant soil growth model. The HERMES model performed well and was able to describe the relevant processes related to soil-plant interactions and the dynamics of mineralization.

The model is a valuable tool in evaluating strategies that can improve agricultural practices in the NCP, both in terms of N fertilization as well

as irrigation practices. The modelling-results show that there is a great potential for improvement of the agricultural system if a more advanced approach to crop cultivation is adopted.

In order to make the model available for the scientific community and extension services in China, a long-term regionalization approach using this model on a county scale in the NCP is currently being pursued. To facilitate the acceptance and use of the model, a Chinese language user-interface version has been developed for HERMES and will be made available to the scientific community.

Finally, the results of this thesis show that urea, the main N source in China, may have a strong priming effect on the activity of microbial organisms, thereby increasing soil respiration and increasing the risk of N loss in the form of N_2O , especially when the soil is amended with the residues of cereal crops. These are important results in terms of estimating the potential of reducing greenhouse gas emissions from agricultural fields.

The urease inhibitor nBPT, by restricting the hydrolysis of urea, not only reduces the loss of N in the form of ammonia, but also reduces the loss of N as nitrous oxide. At the same time, it appears that nBPT does not restrict the rate of nitrification significantly, implying that the chemical may be useful in preventing N loss while maintaining the availability of applied N for plants.

The results of this research warrant further investigations on the subjects

of N mineralization potential in previously over-fertilized agricultural fields and in the use of chemical inhibitors for improving N use efficiency and reducing N loss.

The scientific community has long stressed the immediate need of improving the agricultural system of the NCP. This research shows that, while there is a definite cause for concern, solutions for improving N management exist.

If a communication of scientific results to farmers can be achieved, there is a clear chance that the effect of current agricultural practices on the environment can be reduced.

Summary

The North China Plain (NCP) is the main production area of cereal crops in China. The intensification of agricultural systems and the increased use of chemical N fertilizers are contributing to environmental pollution. In combination with increased industrial activities this development has caused detrimental effects on the environment and on human health.

One of the objectives of this thesis was to apply an N_{\min} based approach for the calculation of N application rates to a previously over-fertilized farmer's field of the NCP and to evaluate the potential of reducing N inputs while maintaining the grain yield of a summer-maize / winter-wheat double-cropping system; and to evaluate fertilizer strategies, aiming to reduce N inputs and loss, regarding their effect on fertilizer N use, grain yields and N use efficiency. A 2.5 year field experiment (3 * maize; 2 * wheat) was conducted in Quzhou County, China, in order to compare 6 optimized strategies of N fertilization to current farmers' practice (FP).

The results of this experiment showed that, using an N_{\min} based approach for the calculation of fertilizer application rates, a reduction of fertilizer input by up to 50% compared to farmers' practice (550 kg N ha⁻¹ a⁻¹) is possible without negatively affecting the grain yield of a wheat / maize double cropping system.

The extreme re-supply of N during the summer-vegetation periods of maize in the first two experimental seasons resulted in high yields of the control treatment (CK: 2009: 5.7 and 2010: 5.9 Mg ha⁻¹), which did not significantly differ from the fertilized treatments. This resulted in a reduced recovery efficiency of N (RE_N: 0.09 kg kg⁻¹ – 0.30 kg kg⁻¹). According to the results of this field experiment there was no agronomic justification for the application of fertilizer N in terms of yield development in these first two years. The grain yield of maize of the control treatment finally decreased in the third vegetation period of summer-maize. While maintaining the yield level, the optimized application of N increased RE_N (0.37 – 0.58 kg kg⁻¹) significantly compared to farmers' practice (0.21 kg kg⁻¹) in this final vegetation period of maize. Wheat, in contrast to maize, is dependent on the application of fertilizer N for yield formation. In both vegetation periods of wheat, RE_N of the reduced treatments (0.34 – 1.0 kg kg⁻¹) was significantly higher compared to FP (0.26 and 0.27 kg kg⁻¹). The highest cumulated (5 vegetation periods) agronomic efficiency of N, as well as cumulated grain yield of the wheat / maize double-cropping system was observed when ammonium sulphate nitrate was applied in combination with the nitrification inhibitor 3,4-dimethylpyrazolephosphate (ASN_{DMPP}: AE_N: 19 kg kg⁻¹, yield: 35 Mg ha⁻¹) and according to crop N demand and residual soil mineral N. The highest RE_N was observed when urea ammonium nitrate was applied in a shallow, banded depot

(UAN_{DEP}: 40 kg kg⁻¹).

The results of this field experiment further show that the N surplus (fertilized N - grain N) as well as the N balance (N Input - N output) after harvest are significantly lower when an optimized approach to fertilizer application is followed. The over-application of N for an optimized application of urea or ASN_{DMPP} (Surplus: -25kg to 98 kg N ha⁻¹; Balance: -36 to 102 kg N ha⁻¹) was significantly reduced compared to current farmers' practice (Surplus: 156kg to 187 kg N ha⁻¹; Balance: 56 to 262 kg N ha⁻¹). This leads to lower residual N in the soil horizon from 0 - 90 cm in the reduced treatments (113 kg N ha⁻¹ at end of experiment) compared to FP (293 kg N ha⁻¹).

The mineralization of N takes place mainly during the summer-vegetation period. The results of this experiment indicate that N contained in the residues of maize is available only to the subsequent summer-crop and may sufficiently supply N for the yield formation of maize. Should the over-application of N be effectively reduced in the cropping systems of the NCP it is therefore necessary to take the N mineralization potential of soils into account.

Based on the results of this field experiment and others, a crop-soil interface model (HERMES) was calibrated and validated to the conditions of the NCP. This model was used to evaluate an N_{min} based approach to fertilizer application and to produce real-time N fertilizer recommendations (NFR) for the NCP. The model can be used to

evaluate optimized agricultural practices (N and water management) for the NCP, aiming to reduce N application rates and subsequent N loss.

Finally, this research observed the effect of wheat straw and the urease inhibitor (UI) N-(n-butyl) thiophosphoric triamide (nBPT) on the turnover of urea, as well as the loss of ammonia and nitrous oxide from an alkaline soil of the NCP.

The essential findings of this research are that UI inhibit or reduce the appearance of ammonia after the application of urea and almost completely prevent the loss of N as ammonia (urea: 12 – 14% loss). nBPT effectively reduces the rate of urea hydrolysis but does not down-regulate the process enough to completely inhibit nitrification, thereby maintaining the availability of N from urea for plants. Further, the addition of wheat straw prolongs the appearance of ammonium after the application of urea while the appearance of nitrate is reduced. Wheat straw may therefore either act as a stimulant of hydrolysis or as an inhibitor of nitrification. The addition of urea increases soil respiration and the emission of N_2O drastically, possibly acting as a C and N source for microbial organisms and causing a priming effect on microbial activity in soils. This effect was increased further when wheat straw as well as urea were added to soil. nBPT, in contrast, prevents a significant increase in CO_2 -respiration and N_2O -emission. The urease inhibitor may therefore generally restrict microbial activity or shift nitrification/denitrification processes towards the emission of N_2 .

Based on these results further research is warranted. Further insight is needed on the extent of N mineralization in previously over-fertilized fields of the NCP in order to evaluate methods for reducing the environmental impact of N. Research on the functioning of the urease inhibitor (nBPT) is necessary to understand its effect on microbial activity.

Zusammenfassung

Die Nordchinesische Tiefebene (NCP) ist Chinas Hauptanbaugelände für Getreide. Die Intensivierung der Landwirtschaft und der steigende Einsatz chemischer Düngemittel tragen wesentlich zur Umweltverschmutzung in China bei. In Verbindung mit der zunehmenden Industrialisierung des Landes hat diese Entwicklung einen verheerenden Einfluss sowohl auf die Umwelt als auch auf die Gesundheit der Bevölkerung.

Ein Ziel dieser Arbeit war es, ein N_{\min} -basiertes System zur Ermittlung des Düngedarfs in einer typischen Weizen / Mais Doppelfruchtfolge der NCP anzuwenden. Hierbei sollte das Potential zur Verringerung der Stickstoff (N-)Einträge bei gleichzeitigem Beibehalt der Ertragserwartungen abgewägt werden. Außerdem wurden Strategien, die eine Verringerung sowohl der N-Einträge als auch Verluste zum Ziel haben, mit der gängigen landwirtschaftlichen Praxis (FP) in Hinsicht auf N-Einträge, Ertrag und N-Nutzungseffizienz verglichen. Hierzu wurde über 2.5 Jahre (3 * Mais; 2 * Weizen) ein Feldversuch in einem ehemals überdüngten Feld der NCP durchgeführt.

Die Anwendung eines N_{\min} -basierten Systems zur N-Bedarfsermittlung lässt im Vergleich zur gängigen landwirtschaftlichen Praxis eine Verringerung des N-Düngeaufwands um 50% zu, ohne den Ertrag der Weizen / Mais Doppelfruchtfolge zu verringern. Eine extrem hohe

Remineralisation von N führte in den ersten zwei Anbauperioden von Mais zu hohen Erträgen der Kontrollbehandlung (CK: 2009: 5.7 und 2010: 5.9 Mg ha⁻¹). Diese Erträge unterschieden sich nicht signifikant von den gedüngten Behandlungen des Versuchs. Aus diesem Grund wurde in den gedüngten Varianten eine sehr geringe N Wiederfindungseffizienz (RE_N : 0.09 kg kg⁻¹ – 0.30 kg kg⁻¹) ermittelt. Aus agronomischer Sicht war eine N-Gabe in den ersten zwei Anbauperioden von Mais nicht notwendig. Erst in der dritten Anbauperiode von Mais wurde ein Ertragseinbruch der Kontrollbehandlung beobachtet. Die optimierte N-Düngung führte im Vergleich zu FP (0.21 kg kg⁻¹) zu signifikant höheren N-Nutzungseffizienzen (0.37 – 0.58 kg kg⁻¹). Im Gegensatz zu Mais ist Winterweizen zur Ertragsentwicklung auf eine N-Gabe angewiesen. Der N_{min} -basierte Ansatz zur Ermittlung des Düngebedarfs führte im Vergleich zu FP (0.26 and 0.27 kg kg⁻¹) zu einer signifikant gesteigerten N Wiederfindungseffizienz (0.34 – 1.0 kg kg⁻¹). Die Ermittlung der kumulierten Erträge und agronomischen Nutzungseffizienz zeigte, dass eine optimierte N-Gabe mit Ammonsulfatsalpeter (ASN) in Verbindung mit dem Nitrifikationshemmstoff 3,4-dimethylpyrazolephosphate (DMPP) mittelfristig die höchsten Erträge sowie agronomische N Effizienz aufwies (ASN_{DMPP} : AE_N : 19 kg kg⁻¹, Ertrag: 35 Mg ha⁻¹). Die höchste Wiederfindungseffizienz wurde bei einer Depotdüngung mit Ammoniumnitrat-Harnstofflösung ermittelt (UAN_{DEP} RE_N : 0.40 kg kg⁻¹).

1).

Die optimierte N-Düngung verringert die N Bilanz nach der Ernte. Die optimierte Düngung von Harnstoff oder ASN_{DMPP} führte zu signifikant verringerten N Bilanzen (-36 to 102 kg N ha⁻¹) im Vergleich zu FP (56 to 262 kg N ha⁻¹). Hierdurch verringerte sich die Überschuss an N im Boden (Urea und ASN_{DMPP} : 113 kg N ha⁻¹ ; FP: 293 kg N ha⁻¹; Versuchsende). N Mineralisation findet hauptsächlich in der Vegetationsperiode von Mais im Sommer statt. Die Ergebnisse dieses Feldversuchs weisen darauf hin, dass N in den Ernterückständen von Mais nicht der dazwischen angebauten Weizenkultur, sondern erst der folgenden Maisfrucht zur Verfügung steht. Die N Mineralisationsrate reicht hier für die Ertragsbildung von Mais aus. Um die Überdüngung mit N effektiv zu verringern, ist es somit notwendig das Mineralisationspotential überdüngter Böden zuverlässig zu bestimmen. Auf Grundlage der Ergebnisse von diesem und weiteren in der NCP durchgeführten Feldversuchen wurde das Boden-Pflanze Interaktionsmodell HERMES am ZALF Müncheberg kalibriert und validiert. Das Model bildete die Prozesse des Bodens und Pflanzenwachstums zuverlässig ab, und kann auf Basis der eingegebenen Daten eine N Düngeempfehlung errechnen. Das Model ermöglicht die Evaluierung optimierter Bewirtschaftungsmethoden die auf eine Verringerung der N Einträge sowie N Verluste abzielen.

In einem Laborversuch wurde der Einfluss von Weizenstroh und dem

Urease-Inhibitor (UI) N-(n-butyl) thiophosphortriamid (nBPT) auf die Umsetzung von Harnstoff, sowie die gasförmigen Emissionen von Kohlenstoffdioxid (CO₂), Lachgas (N₂O) und Ammoniak (NH₃) untersucht.

Die Ergebnisse dieser Forschung zeigen, dass nBPT die Umsetzung von Harnstoff zu Ammonium (NH₄⁺) stark verringert und NH₃ Verluste über einem Zeitraum von 2 Wochen fast vollständig verhindert (Harnstoff: 12 – 14% Verlust). Die Umsetzung des Harnstoff wird hierbei jedoch nicht so sehr verlangsamt als dass die Nitrifikationsrate stark beeinflusst wird. Dadurch ist die Verfügbarkeit von N für Pflanzen nach einer Harnstoffgabe gewährleistet.

Des Weiteren weisen die Forschungsergebnisse darauf hin, dass Weizenstroh das Auftreten von NH₄⁺ verlängert, und das Auftreten von Nitrat (NO₃⁻) verringert. Weizenstroh könnte somit entweder die Hydrolyse des Harnstoff stimulieren oder als Nitrifikationsinhibitor (NI) agieren. Harnstoff steigerte die Bodenrespiration und Emission von N₂O. Unter Zugabe von Weizenstroh kam es zu einer Interaktion der Haupteffekte des Versuchs und einer um Faktor 5 gesteigert N₂O-Emission. Die Ergebnisse weisen darauf hin, dass Harnstoff als C und N Quelle für Mikroben fungiert und die mikrobielle Aktivität antreibt. NBPT verhinderte jedoch diesen Interaktionseffekt. Somit verhindert nBPT entweder das “Priming” der mikrobiellen Aktivität oder es verschiebt die Nitrifikations/Denitrifikationsprozesse zum Verlust von N

als N₂.

Die Ergebnisse dieser Forschung geben Anlass zu einer weitergehenden Beschäftigung mit den Prozessen der Mineralisation in überdüngten Feldern der NCP. Außerdem ist eine tiefere Kenntnis über die Funktion des Harnstoff in Böden, sowie dessen Einfluss auf die mikrobielle Aktivität notwendig.

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There are no words through which I can sufficiently express my gratitude to the many people that have enabled me to get this far. Nevertheless, I shall try:

My supervisors, both in Germany and China have been supportive and immeasurably helpful throughout.

I would especially like to thank my Professor, Torsten Müller. I am very grateful for everything I have learned from him. I would also like to thank him for his encouragement, support and for keeping me from starving for all these years.

I would also like to thank Dr. Rudolf Schulz for staying critical and for sharing my distaste of winter, and my Professors in China, Chen Xinping and Zhang Fusuo, for always making me feel like a welcome member of their working group.

At the former Institute of Plant Nutrition, I must thank all my colleagues, but especially Frau Schöllhammer and Frau Berghammer, who keep the system running. They are great.

It is hard not to be infected by Marco Roelcke's enthusiasm. To him, therefore: thanks!

I am extremely grateful to have had Volker Römheld as a teacher. He taught me to be open not only to new ideas, but to be open to life.

Being abroad for extended periods of time is not always easy - having friends helps. These I found in my dear colleagues Yue Shanchao, Meng Qingfeng, Hou Peng and Wang Zhengrui. They taught me that, sometimes, all it takes is to share good food, a drink and maybe a song.

Also, I am grateful to my friends in the BMBF and IRTG projects: Alex, Sebastian, Orthrud, Torsten, Hannah, Gregor, Max, Anna, Anne, Daniela and Lisa. For exploring the cities with me, at day and night, for sharing my experiences and for, mostly, trying new things.

My flatmates in Stuttgart bore me when I was unbearable, so I have come to regard them as family: I owe more than one dinner to Stefan, Thomas, Julie, Gabriel, Moritz, Johanna and Björn.

And also: Isabel, Sabine, Christian, Anne, Shirel, Katie and Till. I am blessed, having such friends.

I have not forgotten my family. I love them - and I hope they know

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