Biogeosciences Discuss., 11, 2639–2664, 2014
www.biogeosciences-discuss.net/11/2639/2014/
doi:10.5194/bgd-11-2639-2014

Biogeosciences
Discussions
Open Access

Determining the optimal nitrogen rate for summer maize in China by integrating agronomic, economic, and environmental aspects

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Received: 26 November 2013 – Accepted: 4 February 2014 – Published: 14 February 2014

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Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

The concept of high yield with a goal of minimum environmental cost has become widely accepted. However, the trade-offs and complex linkages among agronomic, economic, and environmental factors are not yet well understood. In this study, reactive nitrogen (Nr) losses were estimated using an empirical model, and an economic indicator and an evaluation model were used to account for the environmental costs of different Nr losses after N fertilizer application. The minimum N rate to achieve the maximum yield benefit (agronomically optimal N rate), maximum economic benefit (economically optimal N rate: economic benefit was defined as yield benefit minus N fertilizer cost), and maximum net benefit (ecologically optimal N rate: net benefit was defined as yield benefit minus N fertilizer and environmental costs) were estimated based on 91 on-farm experiment sites with five N levels for summer maize production on the North China Plain. Across all experimental sites, the agronomically, economically, and ecologically optimal N rates (N_{agr}, N_{eco}, and N_{ecl}, respectively) averaged 289, 237, and 186 kg N ha^{-1}, respectively. N_{ecl} management increased net benefit by 31 % with a 45 % decrease in Nr loss intensity (44 %, 60 %, and 33 % for N_2O emission, N leaching, and NH_3 volatilization, respectively) and maintained grain yield, compared to N_{agr} management. Compared to N_{eco} management, N_{ecl} increased net benefit by 6 %, with a 27 % decrease in Nr loss intensity, and maintained economic benefit and grain yield. No differences in N_{ecl} were observed between soil types or years, but significant variation among counties was revealed. N_{ecl} increased with the increase in N-derived yield with an R^2 of 0.80. In conclusion, N_{ecl} was primarily affected by N-derived yield and could enhance profitability as well as reduce Nr losses associated with the maize grain yield.

1 Introduction

Nitrogen (N) is a crucial nutrient that requires careful management in intensive cropping systems because of its diverse beneficial and detrimental effects (Ju and Christie, 2011). Worldwide, N has contributed to higher yields and economic returns to farmers, but it has also been estimated that more than 50 % of applied N remains unutilized, leading to losses of billions of US dollars (Raun and Johnson, 1999). Meanwhile, the massive amounts of N that have leached into water bodies, or been lost into the atmosphere through ammonia volatilization or nitrification–denitrification (Zhu and Chen, 2002), have contributed to various environmental problems, such as the greenhouse effect, eutrophication, and soil acidification (Davidson, 2009; Guo et al., 2010; Ju et al., 2009; Reay et al., 2012; Zhang et al., 1996). In the future, to double crop production, global N fertilizer use will increase by 110–130 % from 2000 to 2050 (Cassman and Pingali, 1995; Galloway et al., 2004; Tilman et al., 2001). Therefore, it is necessary to resolve the contradictions among grain yield, economic benefit, and environmental cost, forming solutions to improve N management strategies agronomically, economically, and environmentally.

In China, the pursuit of high grain yields has been the top priority in policy and in practice (Meng et al., 2012). Thus, current research on improving N management strategies has recommended N application rates according to input–output relationships (such as yield–response curves), with the soil–crop system regarded to some extent as a “black box” due to our poor understanding of the complex N cycling processes occurring in soils (Ju and Christie, 2011). With this approach, although notable success has been made in terms of maximizing yield, the overuse of N fertilization has often been encouraged (Cassman et al., 2002; Drinkwater and Snapp, 2007). For example, a typical N application rate was recommended as around 263 kg N ha^{-1} for summer maize farmers on the North China Plain (Cui et al., 2005), whereas the results of region-wide experiments have demonstrated that N rates could be reduced to 158 kg N ha^{-1} without yield losses (Cui et al., 2008).

In the past few decades, N application rates have been further optimized based on combined economic benefits, effects of N use efficiency, and environmental effects (Liang et al., 2008; Xia and Yan, 2011b). Some studies have linked crop yields and fertilizer with economic indicators, with the recommended N rate being calculated as the N fertilizer rate when the price ratio of N fertilizer to crop yield is equal to the first derivative of the yield response function (Zhu, 2006). Wang et al. (2013) indicated a rate of 169 $kg\,N\,ha^{-1}$ for maize cultivation with an agronomic N efficiency of 23 $kg\,kg^{-1}$, 77 % higher than the N practices of typical farmers. Liu et al. (2013) recommended an optimal N rate of 110 $kg\,N\,ha^{-1}$, with a threshold of nitrate-N content in the 0–90 cm soil layer to mitigate the risk of nitrate leaching. In these studies, however, environmental loads were simply reflected by N-use efficiency and prime cost, without detailed consideration of information on environmental performance, such as nitrate pollution in water related to N leaching and NH_3 volatilization, greenhouse effects related to N_2O emission, and soil acidification related to NH_3 volatilization.

In intensive agricultural cropping systems, the soil N cycle becomes complex after the application of N fertilizer (Cui et al., 2013a; Kim et al., 2012), which provides substrates both for crop N uptake and for the soil microorganisms responsible for different reactive N (Nr) losses (Kim et al., 2012). However, increasing the N application rate cannot promise a sustained increase in crop or economic productivity because of diminishing returns (Cassman et al., 2003), whereas the increases in N rate lead to concurrent environmental impacts (Cui et al., 2013a; McSwiney and Robertson, 2005).

Previously, in studies on optimal N rates, environmental effects and agronomic effects have been notably disconnected, although both are clearly linked to N fertilizer inputs (Cui et al., 2013b). Here, we hypothesize that the optimal N rate integrating agronomic, economic, and environmental aspects could maximize grain yield and economic benefits while minimizing Nr loss intensity (unit, $kg\,N\,Mg^{-1}$ grain yield). In this study, an economic indicator and an evaluation model were used to account for the environmental effects of different Nr losses after N fertilizer application (Xia and Yan, 2012). The response curves of N-derived yield, economic benefit, and net benefit to the

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N application rate were provided to assess three N rates, defined as the agronomic, economic, and ecological N rates, respectively (detail described below). Our objectives were to compare grain yield, benefit, and Nr losses among the agronomic, economic, and ecological N rates, and to clarify the variations in the ecological N rate.

2 Materials and methods

2.1 Experimental design

The experiment was conducted on the NCP (North China Plain), which is a major maize-production region. The climate of the study area is warm, subhumid continental monsoon with cold winters and hot summers. Maize is planted at the end of June and matures in early October. The growing degree days (GDD) from maize planting to maturity measure 1500–1700 GDD. Annual precipitation is 500–700 mm, with ∼ 70 % of rainfall occurring during the maize growing season (Ye et al., 2011). No irrigation water is supplied for maize production in this region.

In total, 91 on-farm experiment sites (i.e., in farmers' fields) were used for maize production from 2008 to 2009 in 12 counties of Henan Province, including Hebi, Jiaozuo, Kaifeng, Luoyang, Nanyang, Pingdingshan, Shanmenxia, Shangqiu, Xinxiang, Zhenzhou, Zhoukou, and Zhumadian counties (Supplement Fig. 1). These experimental sites were located between 31° and 36° N latitude and 110° and 117° E longitude, and included 80 % of the counties in this region. All experimental sites received five N treatments with three replicates: 0 N control (N_0), median N rate (MN), 50 % median N rate (50 % MN), 150 % median N rate (150 % MN), and 200 % median N rate (200 % MN). The MN was derived from agronomists' recommendations based on experience and target economic yields (1.1 times the average yield of the past 5 yr), which varied by site. Across all sites, the MN averaged 232 kg N ha^{-1} (120–360 kg N ha^{-1}; Supplement Table 1).

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The experiments were conducted in winter wheat–summer maize rotation systems, and new experimental sites were selected each year. Approximately one-third of the N fertilizer was applied at pre-sowing, and two-thirds was applied at around the six-leaf stage. N was broadcasted as urea by hand with plowing, during pre-sowing, and with deep placement at the six-leaf stage. Soil types included mainly fluvo-aquic soil, cinnamon soil, and red clay (Zhang, 2002).

Plot sizes measured $> 40\,m^2$. Based on soil phosphorus (P) and potassium (K) levels, all plots received appropriate amounts of triple superphosphate (75–150 $kg\,P_2O_5\,ha^{-1}$) and potassium chloride (75–150 $kg\,K_2O\,ha^{-1}$) pre-sowing. As typical fertilizer method in this area (Zhang et al., 2013; Liu et al., 2010), no organic manure was applied at any experimental site. Each field experiment was managed using the individual producer's current crop management practices, except for necessary experimental treatments, such as fertilizer application and grain yield assessment at harvest. Different varieties of maize hybrids were used among experimental sites, with the varieties being selected by the respective farmers. Weeds were well controlled and no obvious water or pest stresses were observed during the maize growing season. Summer maize was planted with a row spacing of 50–70 cm immediately without tillage after winter wheat harvests at the end of June and was harvested in early October. At harvest, at least $8\,m^2$ (two rows, ~ 8 m long) in the middle of each plot was harvested to determine grain and stover biomass weights.

2.2 Estimating the agronomically, economically, and ecologically optimal N rates

2.2.1 Estimating the agronomically optimal N rate

The agronomically optimal N rate (N_{agr}, $kg\,N\,ha^{-1}$) was determined by calculating the first derivative of the N-derived grain yield response curve to the N application rate (Eq. 2) (Bullock and Bullock, 1994), which was described as a quadratic function (Eq. 1)

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(Cassman and Plant, 1992; Dobermann et al., 2000)

$$Y_N = Y - Y_0 = \beta \cdot N + \alpha \cdot N^2 \tag{1}$$

$$N_{agr} = -\beta/2 \cdot \alpha \tag{2}$$

where Y_N is the increase in grain yield response with the addition of N fertilizer application (N-derived yield, $kg\,ha^{-1}$), Y and Y_0 are the grain yields ($kg\,ha^{-1}$) with and without applied N, respectively, N is the N fertilizer application rate ($kg\,N\,ha^{-1}$), and α and β are regression coefficients.

2.2.2 Estimating the economically optimal N rate

The economically optimum N rate (N_{eco}, $kg\,N\,ha^{-1}$) was defined as the N fertilizer rate when the price ratio of N fertilizer to maize yield was equal to the first derivative of the yield response function (Neeteson and Wadman, 1987; Sawyer et al., 2006). That is, the marginal cost of fertilization N is equivalent to the marginal revenue of maize production. From the first derivative of the economic benefit function (Eq. 3), N_{eco} was estimated by (Eq. 4):

$$EB = B_Y - C_N = b \cdot N + a \cdot N^2 \tag{3}$$

$$N_{eco} = -b/2 \cdot a \tag{4}$$

where EB is economic benefit ($\$\,ha^{-1}$) and B_Y and C_N refer to the N-derived yield benefit and the cost of N fertilizer ($\$\,ha^{-1}$), respectively. We averaged the price of N fertilizer for maize as $710\,\$\,t^{-1}$ from an investigation of county fertilizer dealers in this experimental region from 2008 to 2009. The average maize price adopted of $360\,\$\,t^{-1}$ was released by the Chinese government (http://www.sdpc.gov.cn/). a and b are regression coefficients.

2.2.3 Estimating the ecologically optimal N rate

Considering yield benefit, the cost of N fertilizer, and environmental costs, the ecologically optimal N rate was defined as the N fertilizer rate with maximum net benefit, which equals the revenue of N-derived maize production minus the costs associated with N fertilizer and the cost to the environment, described as follows:

$$\mathrm{NB} = B_\mathrm{Y} - C_\mathrm{N} - C_\mathrm{e} = A \cdot \mathrm{N} + B \cdot \mathrm{N}^2 \tag{5}$$

$$\mathrm{N}_\mathrm{ecl} = -B/2 \cdot A \tag{6}$$

where NB is the net benefit ($\$\,\mathrm{ha}^{-1}$) and C_e is the environmental cost associated with Nr losses.

Various Nr losses (e.g., NH_3 volatilization, N_2O emission, and N leaching) result in different environmental problems, which were quantitatively estimated using a damage cost method in this study (Moomaw and Birch, 2005; Xia and Yan, 2012). Here, the environmental damage cost (C_e, $\$\,\mathrm{ha}^{-1}$) consisted of the costs of greenhouse gas damage to air resources, eutrophication damage to water resources, and acidification damage to soil resources. Detailed descriptions of how to estimate these various environmental costs are shown in Eqs. (7)–(9).

$$C_\text{global warming} = \mathrm{N_2O{-}N} \cdot 44/28 \cdot 298 \cdot P_g \tag{7}$$

where $C_\text{global warming}$ is the global warming cost of greenhouse gas damage to air resources, $N_2O{-}N$ is the N lost by N_2O emissions ($\mathrm{kg\,N\,ha^{-1}}$), 44/28 is a factor to convert kg N to kg N_2O, 298 is the CO_2-equivalent on a 100 yr timescale for the global warming potential of 1 kg N_2O (Forster et al., 2007), and P_g is the market price of CO_2, set at 23.8 $\$\,\mathrm{t}^{-1}$ for 2008 (Xia and Yan, 2011a).

$$C_\text{eutrophication} = [(0.42 \cdot \mathrm{NO_3{-}N}) + (0.33 \cdot \mathrm{NH_3{-}N} \cdot 17/14)] \cdot P_\mathrm{e} \tag{8}$$

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where $C_{\text{eutrophication}}$ is the cost of eutrophication damage to water resources, $NO_3{-}N$ and $NH_3{-}N$ are the N lost by $NO_3{-}N$ leaching and ammonia volatilization, respectively (kg N ha^{-1}), 0.42 and 0.33 are the PO_4 equivalent eutrophication for $NO_3{-}N$ and NH_3, respectively (Goedkoop, 1995), 17/14 is a factor to convert kg N to kg NH_3, and P_e is the equivalent cost of PO_4, set at 0.6 \$ kg^{-1} in eutrophication (Xia and Yan, 2011a).

$$C_{\text{acidification}} = NH_3{-}N \cdot 17/44 \cdot 1.88 \cdot P_a \tag{9}$$

where $C_{\text{acidification}}$ is the cost of acidification damage to soil resources, $NH_3{-}N$ is the N lost by ammonia volatilization (kg N ha^{-1}), 17/14 is a factor to convert kg N to kg NH_3, 1.88 is the SO_2-equivalent acidification for NH_3 (Goedkoop, 1995), and P_a is the cost per kg of SO_2-equivalent, as 0.82 \$ kg^{-1} in acidification (Xia and Yan, 2011a).

In this study, the losses of $N_2O{-}N$, $NO_3{-}N$, and $NH_3{-}N$ described above in Eqs. (7)–(9) were estimated with the N_{rate}-based empirical models (Eqs. 10–12) adopted for summer maize in the study region (Cui et al., 2013a).

$$N_2O{-}N = 0.48 \cdot \exp(0.0058 \cdot N) \tag{10}$$

$$NO_3{-}N = 4.46 \cdot \exp(0.0094 \cdot N) \tag{11}$$

$$NH_3{-}N = 0.24 \cdot N + 1.30 \tag{12}$$

2.3 Data analysis

To establish the N-derived yield, economic benefit, and net benefit response curves to the N rate, *t* tests were used to examine the significance of the regression coefficients and intercepts in fitted parametric models, and the coefficients of determination (R^2) for fitted parametric models were used as the criteria for model selection: models with higher R^2 values were selected. A one-way analysis of variance (ANOVA; Guarda et al., 2004) was used to compare the mean N rate, grain yield, benefit, and loss among N_{agr}, N_{eco}, and N_{ecl} managements, and among different soil types, years, and counties,

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based on the least significant difference (LSD) at a 5 % level of probability. These statistical analyses were conducted using SPSS 13.0 (SPSS Inc., Chicago, IL, USA) and SigmaPlot 10.0 (Systat, San Jose, CA, USA).

3 Results

3.1 Comparison of agronomically, economically, and ecologically optimal N rates

Across all 91 experimental sites, the grain yield for the N_0 treatment averaged 6.6 Mg ha^{-1} and varied from 3.2 to 10.8 Mg ha^{-1} (Supplement Table 1 and Table 1). The MN across all 91 fields averaged 231 kg N ha^{-1} and varied from 120 to 240 kg N ha^{-1}, and the grain yield averaged 8.4 Mg ha^{-1} and varied from 5.4 to 11.9 Mg ha^{-1}. Under the 50 % MN treatment (average 115 kg N ha^{-1}), grain yield decreased by 8.5 %, while it decreased by 7.5 % under the 200 % MN treatment (average 462 kg N ha^{-1}). These results indicated that both overuses and deficits in N application resulted in lower grain yields.

Across all sites and N treatments, the N-derived grain yield averaged 1.5 Mg ha^{-1} in response to additional N application, varying from −0.5 to 4.1 Mg ha^{-1}, while the economic benefit averaged 318 $ ha^{-1} and varied from −513 to 1319 $ ha^{-1}. The environmental cost averaged 202 $ ha^{-1}, including 32, 41, and 129 $ ha^{-1} for the costs of global warming, eutrophication, and soil acidification, respectively (Supplement Table 2 and Fig. 1). Over all sites and N treatments, the net benefit averaged 116 $ ha^{-1} and varied from −894 to 1171 $ ha^{-1}.

For all 91 sites, the N-derived yield, and economic and net benefit responses to increasing the amount of N applied were preferably simulated by quadratic functions (Figs. 1 and 2; $p < 0.05$). The minimum N rate to achieve the maximum yield benefit (N_{agr}), maximum economic benefit (N_{eco}), and maximum net benefit (N_{ecl}) averaged 289, 237, and 186 kg N ha^{-1}, respectively (Table 2). Compared to N_{agr} management,

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the net benefit for N_{ecl} management increased by 31 % from 364 to 345 $ ha^{-1} with a 0.2 Mg ha^{-1} decrease in grain yield while maintaining economic benefit at 456 $ ha^{-1}. Correspondingly, the total Nr loss intensity decreased by 45 %, and N_2O emission, N leaching, and NH_3 volatilization were reduced by 44 %, 60 %, and 33 %, respectively. No significant differences were observed in grain yield, or economic or net benefit between N_{ecl} and N_{eco} management, while total Nr loss intensity was reduced by 27 %, including 24 %, 37 %, and 20 % for N_2O emission, N leaching, and NH_3 volatilization, respectively. These results indicated that applying an appropriate N rate could significantly decrease Nr losses while maintaining both maximum grain yield and farm profitability.

3.2 Variation in the ecologically optimal N rate

Across all 91 experimental sites, the N_{ecl} ranged widely from 65 to 288 kg N ha^{-1} with a coefficient of variation (CV) of 29 % (Supplement Table 2). No differences were observed in N_{ecl} among different soil types, with 189, 178, and 185 kg N ha^{-1} for fluvo-aquic soil, cinnamon soil, and red clay, respectively. Year also did not significantly affect N_{ecl}, which measured 194 and 181 kg N ha^{-1} in 2008 and 2009, respectively. Significant differences in N_{ecl} occurred among counties (Fig. 3a). For example, the lowest N_{ecl} was 151 kg N ha^{-1} in Nanyang County, whereas the N_{ecl} was 56 % higher at 236 kg N ha^{-1} in Shangqiu County. Similarly, large differences were observed among sites in each county (Supplement Table 2). For example, in Hebi County, the lowest N_{ecl} was 71 kg N ha^{-1} at site 1, compared with the highest of 235 kg N ha^{-1} at site 11.

Correspondingly, grain yield, control yield, and N-derived yield showed no differences among different soil types or years, but were significantly affected by county (Fig. 3b–d). For example, in Pinddingshan County, grain yield and control yield were the lowest at 5.8 and 3.9 Mg ha^{-1}, 61 % and 49 %, respectively, lower than those in Hebi County. The N-derived yield in Nanyang County measured 1.1 Mg ha^{-1}, while the highest, in Zhumadian County, showed a 150 % increase at 2.7 Mg ha^{-1}. Such notable variations

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were also observed among sites in each county (Supplement Table 2). For example, within N_{ecl} in Hebi County, the lowest N-derived yield was 0.3 Mg ha^{-1} at site 1, while the highest was 2.3 Mg ha^{-1} at site 9.

No significant correlation was observed between grain yield and $N_{ecl,}$ despite the large variations in both (Fig. 4a). N_{ecl} significantly decreased with an increase in control yield with an R^2 of 0.26 (Fig. 4b), and increased with increasing N-derived yield with a higher R^2 of 0.80 (Fig. 4c). These results indicated that N_{ecl} was primarily affected by the N-derived yield.

4 Discussion

The efficient use of N fertilizer is essential to increasing the economic returns of maize production and minimizing the potential negative effects of N on soil, water, and air quality, especially in intensive agricultural systems (Chen et al., 2010). Current N management strategies have been aimed at determining regional N_{eco} to maximize profits (Scharf et al., 2005; Williams et al., 2007). For summer maize production on the NCP, N fertilizer application rates of 223–240 kg N ha^{-1} for intensive maize systems have been recommended by public documents guiding fertilization (Liu, 2009) or study research (Wang et al., 2012). These recommended N application rates are similar to the 237 kg N ha^{-1} found for N_{eco} in the present study. With N_{eco} management, the grain yield averaged 8.5 Mg ha^{-1}, and estimated N uptake averaged 170 kg N ha^{-1} (based on 2.0 kg N Mg^{-1} grain; Yue, 2013), which is significantly lower than the 237 kg N ha^{-1} found for N_{eco} in the present study. This large N surplus drives high Nr losses and environmental pollution problems, such as the greenhouse effect, eutrophication, and soil acidification (Davidson, 2009; Guo et al., 2010; Ju et al., 2009; Reay et al., 2012; Zhang et al., 1996). These problems and their consequences are meaningful on a global scale.

For current intensive maize systems, when the greenhouse effect, eutrophication, and soil acidification associated with the N application were considered, N_{ecl} was

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reduced by 22 % to 186 $kg\,N\,ha^{-1}$, compared with the current N_{eco}. As a result, this N_{ecl} management strategy reduced Nr loss intensity without significant decreases in grain yield or economic benefit. Similar results were reported for other cereal crop systems. Xia and Yan (2011a) used published field experiment measurements to establish grain yield and environmental cost response curves to the N application rate; they gave N_{ecl} as 205 $kg\,N\,ha^{-1}$ for wheat production in the Taihu Lake region of China, which was 21 % lower than the economically optimal N rate of 258 $kg\,N\,ha^{-1}$ and decreased Nr losses by 28 %. For rice in the same region, the N_{ecl} was 202 $kg\,N\,ha^{-1}$, 23 % lower than the economically optimal N rate of 263 $kg\,N\,ha^{-1}$, with a 29 % decrease in Nr losses (Xia and Yan, 2012).

Aside from the negative environmental effects, N application rates could be also optimized based on the concept of willingness to pay (WTP) for human health and ecosystem services. Brink et al. (2011) estimated that excess N in the environment costs the European Union between 100 and 460 billion $\$\,yr^{-1}$, of which ~ 75 % is related to health damage and air pollution, and suggested that the socially optimal N rate would lower the farm (private) optimal N rate by 50 $kg\,N\,ha^{-1}$ (35–90 $kg\,N\,ha^{-1}$) for winter wheat and oilseed rape. Another study based on life-cycle assessment showed a decrease in the optimal N rate of 50–100 $kg\,N\,ha^{-1}$ for winter wheat in the UK (Brentrup et al., 2004).

In the present study, the large variations in ecologically optimal N rates (from 65 $kg\,N\,ha^{-1}$ at site 14 in Luoyang County to 288 $kg\,N\,ha^{-1}$ at site 2 in Xinxiang County; Supplement Table 2) demonstrate the difficulties of ecological N management. Similar wide ranges in optimal N rates both among fields (Bundy and Andraski, 1995; Cui et al., 2008) and within fields (Mamo et al., 2003; Scharf et al., 2005) have been reported in other studies. In the present study, N_{ecl} increased with increases in N-derived yield (Fig. 4c), which was mostly associated with the high variability in farmers' practices. Similar results were reported for spring maize systems in China (Gao et al., 2012). In the present study region, which represents a typical maize production area of China, each farmer operates on < 1 ha of land. This small-scale farming with high variability between fields and poor infrastructure has reduced the efficiency

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of current science-based management tools and technological practices in China (Cui et al., 2010). Additionally, older and less-educated individuals frequently work in farming, and many educated young farmers have left the industry (Barning, 2008; Huang et al., 2008), which has been thought to contribute to the variation in farm practices. In the future, training and motivating farmers to improve crop management with increasing N-derived yields would help to implement ecological N management.

Note that the present estimates of N_{ecl} in this region (Supplement Table 2 and Table 2) are far from robust due to the uncertainties of estimating different Nr losses and in the N-derived yield benefit response to the N rate. In this study, Nr losses from N fertilization are expressed as a function of the N application rate, indicating that high N application rates always lead to large Nr losses to the environment (Stehfest and Bouwman, 2006). However, Nr losses also depend on some factors other than the N application rate, such as soil type, climate, and N application method (Gregorich et al., 2005). Cui et al. (2013b) indicated an appropriate source, timing, and placement of N fertilizer and related practices, which tend to enhance crop recovery of applied N, increase crop yield, and could also contribute to lowering Nr losses. Thus, environmental factors and crop practices affecting Nr losses should be taken into account to minimize the uncertainty of regional estimations of Nr losses. In addition, the typical small-scale farms with high variability between fields in China contributed to uncertainties in the regional estimation of the N-derived yield benefit response to N rate. For example, within 210 $\mathrm{kg\,N\,ha^{-1}}$, the N-derived yield benefit was 209 $\$\,\mathrm{ha^{-1}}$ at site 1 in Kaifeng County, compared with 1278 $\$\,\mathrm{ha^{-1}}$ at site 2 in Jiaozuo (Supplement Table 2). Therefore, more field experiment data sets should be obtained and a model considering environmental factors, fertilizer, and crop management systems should be used to more accurately determine regional N-derived yield benefit and Nr losses.

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5 Conclusions

A marked increase in N fertilizer consumption is expected to occur worldwide within a few years because of the growing demand for crop production. As demonstrated in this study, the N application rate is an important factor affecting both the economic and environmental performance of corn production. Applying an appropriate N rate could both enhance farm profitability and reduce the Nr losses associated with maize yield. In our study, the N_{ecl} averaged 185 $kg\,N\,ha^{-1}$ across 91 on-farm experimental sites. This ecological N management had the highest net benefit of 345 $\$\,ha^{-1}$, and reduced the N rate by 22 % and Nr loss intensity by 27 %, including 24 %, 37 %, and 20 % for N_2O emission, N leaching, and NH_3 volatilization, respectively, without significant decreases in grain yield as compared with the N_{eco} of 237 $kg\,N\,ha^{-1}$.

The N_{ecl} varied with farming site. The typical small farms with high variability in farming practices resulted in variations of N_{ecl} from 65 to 288 $kg\,N\,ha^{-1}$. To determine a regional N_{ecl}, models considering environmental factors, fertilizer, and crop management strategies should be used to estimate Nr losses accurately, and more field experiment data sets should be obtained to determine the yield benefit responses to the N application rate. In the future, increases in N-derived yield will be important to demonstrate this ecological N management, and training and motivating farmers to use improved techniques will be an essential step.

Supplementary material related to this article is available online at http://www.biogeosciences-discuss.net/11/2639/2014/bgd-11-2639-2014-supplement.pdf.

Acknowledgements. This work was funded by the Special Fund for the Agricultural Profession (201303103), the Program for New Century Excellent Talents in University (NCET-11-0478), and the Innovation Group Grant of the National Natural Science Foundation of China (31121062).

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Table 1. Summary statistics of the N rate and grain yield over 91 sites in 12 counties in Henan Province for maize production in China from 2008 to 2009. MN is the median N rate.

Treatment	N rate $kg\,N\,ha^{-1}$	Grain yield ($Mg\,ha^{-1}$) Mean	SD	Minimum	Maximum	Median	25 % Q	75 % Q
N0	0	6.6	1.6	3.2	10.8	6.7	5.6	7.7
50 % MN	115	7.7	1.5	3.8	11.6	7.9	6.5	8.8
MN	231	8.4	1.3	5.4	11.9	8.5	7.4	9.3
150 % MN	346	8.2	1.5	4.7	12.0	8.4	7.1	9.2
200 % MN	462	7.8	1.4	4.3	11.3	7.8	6.7	8.9

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Table 2. N rate, grain yield, economic benefit, net benefit, and Nr loss intensity with agronomically, economically, and ecologically optimal N rates, respectively, over 91 sites in 12 counties in Henan Province for maize production in China from 2008 to 2009. Different letters to the right of data indicate significant differences at $p < 0.05$.

Item	N rate	Grain yield	Economic benefit	Net benefit	Nr loss intensity ($kg\,N\,Mg^{-1}$ grain)			
	$kg\,N\,ha^{-1}$	$Mg\,ha^{-1}$	$\$\,ha^{-1}$	$\$\,ha^{-1}$	Total	N_2O emission	N leaching	NH_3 volatilization
N_{agr}	289^{a}	8.5^{a}	456^{a}	264^{b}	17.1^{a}	0.32^{a}	8.9^{a}	8.6^{a}
N_{eco}	237^{b}	8.5^{a}	474^{a}	325^{ab}	12.9^{b}	0.24^{b}	5.6^{b}	7.1^{b}
N_{ecl}	186^{c}	8.3^{a}	456^{a}	345^{a}	9.5^{c}	0.18^{c}	3.6^{c}	5.7^{c}

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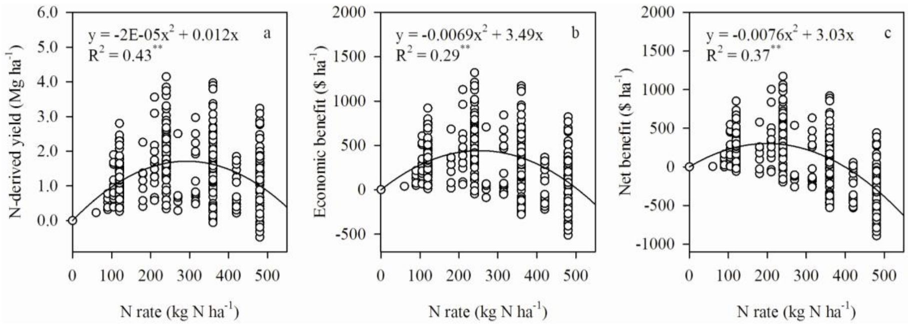

Fig. 1. Relationships between the N rate and N-derived yield **(a)**, economic benefit **(b)**, and net benefit **(c)** over 91 sites in 12 counties in Henan Province for maize production in China from 2008 to 2009. ** Significant at $p < 0.05$.

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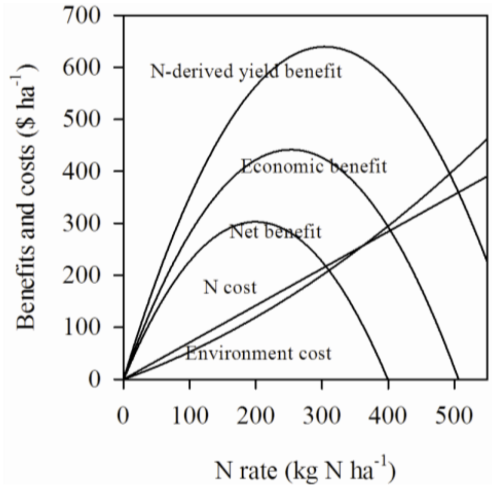

Fig. 2. N-derived yield benefit, economic benefit, net benefit, N fertilizer cost, and environmental cost associated with different N rates over 91 sites in 12 counties in Henan Province for maize production in China from 2008 to 2009.

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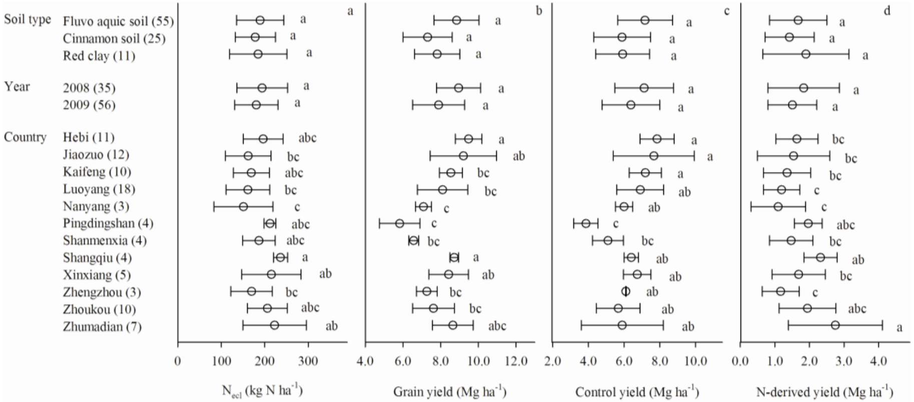

Fig. 3. Average ecologically optimal N rate (N_{ecl}) **(a)**, grain yield **(b)**, control yield **(c)**, and N-derived yield **(d)** when the data were examined by soil type, year, and county, respectively. Error bars indicate the standard deviations of the means of N_{ecl}, grain yield, control yield, and N-derived yield. Different letters to the right of data points indicate significant difference at $p < 0.05$. The numbers of sites in each data group are given in parentheses.

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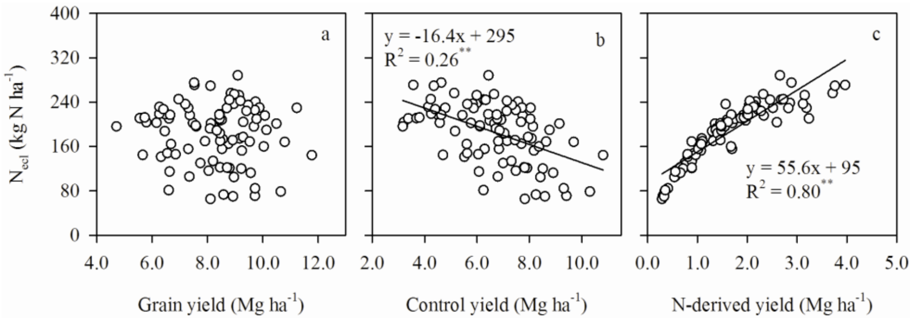

Fig. 4. Relationships between the ecologically optimal N rate (N_{ecl}) and grain yield **(a)**, control yield **(b)**, and N-derived yield **(c)** over 91 sites in 12 counties in Henan Province for maize production in China from 2008 to 2009. ** Significant at $p < 0.05$.