Ecological intensification management of maize in northeast China: Agronomic and environmental response

Article *in* Agriculture Ecosystems & Environment · May 2016

Impact Factor: 3.4 · DOI: 10.1016/j.agee.2016.03.038

7 authors, including:

Ping He

Chinese Academy of Agricultural Sciences

80 PUBLICATIONS **668** CITATIONS

SEE PROFILE

Xinpeng Xu

Chinese Academy of Agricultural Sciences

14 PUBLICATIONS **86** CITATIONS

SEE PROFILE

Shicheng Zhao

Chinese Academy of Agricultural Sciences

13 PUBLICATIONS **92** CITATIONS

SEE PROFILE

Agriculture, Ecosystems and Environment 224 (2016) 123–130

Contents lists available at ScienceDirect

Agriculture, Ecosystems and Environment

journal homepage: www.elsevier.com/locate/agee

Ecological intensification management of maize in northeast China: Agronomic and environmental response

Rongrong Zhao[a,b], Ping He[a,b,*], Jiagui Xie[c], Adrian M. Johnston[d], Xinpeng Xu[a], Shaojun Qiu[a], Shicheng Zhao[a]

[a] *Ministry of Agriculture Key Laboratory of Plant Nutrition and Fertilizer, Institute of Agricultural Resources and Regional Planning, Chinese Academy of Agricultural Sciences (CAAS), Beijing 100081, PR China*
[b] *International Plant Nutrition Institute (IPNI) China Program, CAAS-IPNI Joint Lab for Plant Nutrition Innovation Research, Beijing 100081, PR China*
[c] *Jilin Academy of Agricultural Sciences, Changchun, Jilin 130124, PR China*
[d] *International Plant Nutrition Institute (IPNI), 104-110 Research Drive, Saskatoon SK S7N3R3, Canada*

ARTICLE INFO

Article history:
Received 16 October 2015
Received in revised form 25 March 2016
Accepted 26 March 2016
Available online 7 April 2016

Keywords:
Spring maize system
Ecological intensification
Potential yield
NUE
Greenhouse gas emission

ABSTRACT

Optimum field management practices need to be developed and improved to solve the challenge of increasing food production while retaining the ecological integrity of farming system underlying the goal of sustainable agriculture. In our study, the concept of ecological intensification (EI) was applied to a spring maize cropping system in Jilin province, China during 2009–2013. Results indicated that the average grain yield was 11.8 t ha^{-1} in the EI treatment; while the farmers' practice (FP) treatment had an average of 11.4 t ha^{-1} grain yield across five seasons. The Hybrid Maize Model was used to simulate the potential yield under water-limited condition, and the results showed that grain yield with 92.6% of the average potential yield (14.3 t ha^{-1}) in EI treatment was closer to the yield potential than FP treatment. Adjusted nitrogen (N) fertilizer rate, split-application of N at the right time and suitable recommended hybrid maize plant density were used for improving N use efficiency and decreasing the negative effects to the environment. Consequently, a total of 180 kg N ha^{-1} was enough for maize growth and resulted in equal plant N uptake as the 251 kg N ha^{-1} applied in FP. Higher agronomic efficiency of N (AE_N), recovery efficiency of N (RE_N) and partial factor productivity of N (PFP_N) in EI treatment (39.7 kg kg^{-1}, 66.1% and 66.2 kg kg^{-1}, respectively) were observed relative to those in FP treatments (26.9 kg kg^{-1}, 42.5% and 50.4 kg kg^{-1}, respectively). Improved N use efficiency contributed significantly less N loss to the environment. Our results showed that calculated residual N_{min}, the apparent N loss and total GHG emission was 37.5%, 34.3% and 29.8% lower in EI treatment when compared to FP treatment. This study helps quantify and understand the concept and practices of EI. Adoption of 4R Nutrient Stewardship (fertilizer right source, right rate, time and placement) and supporting agronomic practices (optimizing plant density and plant hybrid selection) in our study optimized crop production and minimized potential environmental impact.

1. Introduction

Global agriculture is facing the challenge of rising world-wide population and massive food demand. This occurs when issues like farmland decline, water resources depletion and insecurity and environmental degradation are gathering increased attention. China is facing the great challenges to feed one fifth of the world's population on less than one tenth of its arable land and limited freshwater resources.

Ecological intensification (EI) was first termed to describe a production system that satisfied the anticipated increase in food demand while meeting acceptable standards for environmental quality by Cassman (1999). Attaining high grain production while minimizing environmental cost by integrating the ecological management practices will be more likely to adopt in the future of China. The key points of EI have been associated with the eco-efficiency and focused on the debate around food production and environmental protection. EI aims to establish common practices based on ecological and evolutionary science (Dension, 2012). The use of EI practices represents a sustainable way of knowledge and

---

* Corresponding author at: Institute of Agricultural Resources and Regional Planning, Chinese Academy of Agricultural Sciences, CAAS. No. 12, Zhongguancun South Street, Beijing 100081, PR China.
E-mail address: heping02@caas.cn (P. He).

http://dx.doi.org/10.1016/j.agee.2016.03.038

technologies in agriculture development which aims to address food security and environmental security. In the last decades, numerous field trials conducted in different sites have demonstrated the eco-efficiency ideas of EI. In recent studies, heterotic hybrids adoption plus the use of fertilizer and herbicide have helped US corn yield increased from 7.1 t ha^{-1} in 1990s to 9.4 t ha^{-1} in 2000s (Flavell 2010). Crop-legume intercropping system has been proved to be a useful component of EI in Mozambique, Africa (Rusinamhodzi et al., 2012). Optimized plant density, fertilizer N and water management could improve rice yield, N and water use efficiency in Amazonia (Gehring et al., 2013). According to these results, scientists and researchers have summarized that EI should be less dependent on non-renewable resources and should maintain soil fertility and biodiversity. To be specific, EI requires efficient use of input (fertilizer, pesticide), optimized practices (irrigation, cropping intensity) and minimal impact on global warming (greenhouse gas emission).

However, past agricultural intensification (e.g., Green Revolution) was mainly connected with negative impacts on natural resources and high environmental cost to solve the staple crop production. In China, the crop production systems have been performed as multiple crop rotation system (maize-wheat, rice-wheat, and rice-rice) since the 1950s. According to Zhang et al. (2011), the average maize yield was as high as 8.5 t ha^{-1} due to the adoption of new maize varieties in the field experiment conducted in northeast China, 37.6% higher than the average yield of 5.3 t ha^{-1} in farmers' field with old varieties. Moreover, the attainable maize yield in northeast China could be as large as 16.8 t ha^{-1} through high inputs of nutrients, water, labor and other additional improvements including crop straw return, no-tillage, and applications of organic manure (Fan et al., 2010). Due to this highly intensification in production systems, Chinese produced more than fourfold the grain production in 2010s compared to 1960s (Bishwajit et al., 2013). The cost for this yield increase is the high-input of fertilizer, pesticides and high environment risks including degradation of land and freshwater, emissions of greenhouse gases and loss of biodiversity (Chen et al., 2014; Davidson 2009; Christopher and Tilman, 2008; Diaz and Rosenberg, 2008; Guo et al., 2010). According to the statistics from China Agriculture Yearbook (2013), an estimated 74.3 Mt chemical fertilizer was consumed to produce 589.6 Mt crop productions in 2012. Fertilizer N application rate increased by 12.2%, 19.1% and 6.4% for wheat, rice and maize from 2000 to 2007 (Li et al., 2010). Meanwhile, low recovery efficiency of nitrogen (RE_N) values were found with values of 28.2%, 28.3% and 26.1% for wheat, rice and maize respectively when compared to the worldwide RE_N value which ranged from 40 to 60% (Zhang et al., 2008; Fan et al., 2012). High chemical fertilizer input, especially fertilizer N, caused great negative effects on environment quality, especially within and adjacent to farm fields and local fresh water. Over 50% of lakes were eutrophic in China, and soil acidification is becoming a major problem from fertilizer N cycling process (Guo et al., 2010).

Maize (*Zea mays* L.) is one of the important cereal crops which plays a significant role in expanding the overall grain production capacity in China. Sufficient yield information has been collected from a large number of farms, but producing higher yields under optimum management condition is far from clear. To date, how to narrow the yield gap between optimal treatment and farmers' practices and improve the attainable yield or achieving similar production levels with integrated management practices or reduced resources input and efficiency are still the challenges which the future of China agriculture is facing. According to Cui et al. (2008a,b), the average on-farm RE_N and partial factor productivity of nitrogen (PFP_N) for maize in the North China Plain were 16% and 37 kg kg^{-1} between 2002 and 2006. However, the average on-farm RE_N value in U.S. Corn Belt was 37%, which is more than twice than that in China (Cassman et al., 2002; Dobermann, 2005). The PFP_N value in some developed countries has been steadily maintained at 49 kg kg^{-1} since 1980s (Dobermann and Cassman, 2005). It was reported that current indigenous N supply was over 270 kg N ha^{-1} yr^{-1} in wheat-maize system in north China, and 90 kg N ha^{-1} of residual nitrate-N after harvest should be the maximum limit in the top 90 cm soil layer for achieving high maize yield (Cui et al., 2008a, 2008c; Cui et al., 2010). In our study, optimal nutrient management based on EI principles in the high-yielding maize cropping system was matched not only in fertilizer quantity and application timing, but was also dependent on improved agronomic practices (including variety, weather conditions and environment impact). Two main treatments were defined in our project. One was EI treatment with a fertilizer rate of 180 kg N ha^{-1} (N180), different N application methods and a higher plant population, which generally represents a trend of new Ecological Intensification of fertilizer N application. On the other hand, one traditional method of "Farmer's Practice (FP)" was defined as a higher fertilization rate in northeast China, average 251 kg N ha^{-1} (N251) with only basal dressing of all N, P and K fertilizer, and a lower plant population of 50,000/ha compared to the EI treatment. Therefore, the objectives of our study were to (1) compare the main differences in yield, N use efficiency and soil N loss from a 5-year period between EI and FP treatment, and (2) evaluate the agronomic and environmental effect of EI practices on grain yield, N efficiency parameters, and N losses and greenhouse gases (GHG) to provide scientific guidance to increase grain yield and N efficiency while minimizing adverse environmental effect.

2. Materials and methods

2.1. On-farm experiment

The long-term field experiment was conducted at Liufangzi County, Gongzhuling City, Jilin province which is located at 43°34.86′ N and 124°53.92′ E. The study area has a temperate and semi-humid continental monsoon climate. The mean annual air temperature is 18.2 °C. The average annual precipitation is 480–600 mm with average 140 days frost-free period. The basic baseline soil test parameters were pH of 6.06, organic matter of 20.4 g kg^{-1}, alkaline-extractable N of 118.2 mg kg^{-1}, Olsen-P_2O_5 75.7 mg kg^{-1} and NH_4OAC-extractable K_2O 122.4 mg kg^{-1}. The field experiments were initiated in the spring of 2009 with four treatments with four replications.

The Nutrient Expert (NE) for hybrid maize was used for fertilizer recommendations for the EI treatment (Pampolino et al., 2012). A series of information required based on five modules in the NE decision support tool, including current farmers' practice, plant density, site-specific nutrient management, and sources and splitting and profit analysis. According to Xu et al. (2014), expected yield response to fertilizer and agronomic efficiencies of applied N were the main determinant factors for fertilizer application rate. The fertilizer rate of 180 kg N ha^{-1}, 75 kg P_2O_5 ha^{-1} and 90 K_2O kg ha^{-1} in EI treatment, which is in accordance with the concept of ecological intensification system and represents a new trend of fertilizer application. Meanwhile, the FP treatment received fertilizer supply of 251 kg ha^{-1} N, 145 kg ha^{-1} P_2O_5 and 100 kg ha^{-1} K_2O from 2009 to 2013 which represent an average fertilizer rate applied in northeast China (Xu et al., 2014). An additional 30 kg S ha^{-1} and 5 kg Zn ha^{-1} was applied to EI based on soil test results to eliminate nutrient deficiencies in 2009. The N rate in the EI treatment with 180 kg ha^{-1} which were one quarter of N, all P_2O_5 and K_2O applied as basal and the remaining N applied for topdressing. FP treatment adopted 251 kg ha^{-1} with all N, P_2O_5 and K_2O applied as basal which was 28.3% higher N rate than in the EI treatment. The adjustment between EI and FP treatment also reflected in that EI treatment adopted a two-time splitting fertilization pattern in the first three years (2009–2011), and then a three-time splitting fertilization at critical planting stages like heading stage and tasseling stage was applied in 2012 and 2013.

The maize hybrid variety Pioneer 335 was used in all years for the EI treatment; Pioneer 335 was used for the first two years, Jidong 33 was used in 2011, and Lvyu 4117 was used in the next two years for FP treatment. Except for the zero N plots, all agronomic practices were kept the same with each respective treatment. Another adjusted practice the EI treatment adopted was to optimize the level of plant density to 65,000 per ha rather than 50,000 per ha in FP treatment.

Fresh soil samples from the top 90 cm (0–5, 5–10, 10–20, 20–30, 30–60 and 60–90 cm) were collected before sowing and after harvest for nitrate-N (NO_3—N) and ammonium-N (NH_4—N) analysis in each year.

2.2. Experiment and data analysis

2.2.1. Data collection

A random sampling area at maturity was selected in each treatment plot to determine grain yield. Generally, two middle lines of maize were chosen in each plot, and ten representative maize plants were selected for moisture content determination, which converted to a standard moisture content of 0.155 kg kg^{-1} H_2O for final grain yield measurement. A set of subsamples of three to five plant samples included grain and straw were dried to constant weight at 70 °C, and then prepared for further nutrient concentration analysis. NO_3—N and NH_4—N concentration measurements from soil fresh samples were extracted with 1:10 ratio of soil to 0.01 mol L^{-1} $CaCl_2$ solution and then analyzed by using continuous flow analysis (Foss FIAstar 5000, Sweden). Soil water content was analyzed using oven dried soil at 105 °C.

2.2.2. Nitrogen use efficiency estimation

Detailed analysis and calculation methods about nitrogen use efficiency parameters included the agronomic efficiency of N (the ratio of yield response to the amount to applied N, AE_N), the recovery efficiency of N (% fertilizer N recovered in above-ground crop biomass, RE_N), accumulated recovery efficiency of N (RE_{Na}), and the partial factor productivity of applied N (the ratio of yield to the amount of applied N, PFP_N),

$$REN = (U - U0)/N \times 100 \quad (1)$$

$$AEN = (Y - Y0)/N \quad (2)$$

$$REN_a = \frac{U_a - U0_a}{N_a} \times 100 \quad (3)$$

$$PFPN = Y/N \quad (4)$$

where U, U0 are crop N uptake for N180 (EI), N251 (FP), and N0 treatments, Y, Y0 are grain yield for N180 (EI), N251 (FP), and N0 treatments, U_a, $U0_a$ are accumulated crop N uptake for N180 (EI), N251 (FP), and N0 treatments, respectively, and N is the fertilizer N application rate, N_a is the accumulated fertilizer N application rate (He et al., 2009; Chuan et al., 2013).

2.2.3. Soil nitrogen balance estimation

We also calculated soil apparent N loss which is a soil N balance indictor during the growing season based on method from Zhao et al. (2006) and the key equations are listed below:

$$\text{Apparent N loss} = \text{N input} - \text{N output} \quad (5)$$

$$\text{N input} = \text{initial soil } N_{min} + \text{fertilizer N} + \text{apparent } N_{min} \quad (6)$$

$$\text{N output} = \text{crop N uptake} + \text{residual soil } N_{min} \quad (7)$$

$$\text{Apparent } N_{min} = (\text{N output} - \text{initial soil } N_{min})\ \textit{at N0 plot} \quad (8)$$

2.3. Weather data collection and GHG emission estimation

Based on the elevation and site location, weather data includes maximum, minimum daily temperature, solar radiation, precipitation amount and wind speed of each day from 2009 to 2013 were collected from weather ground station at Liufangzi County, Changchun, Jilin province. Rainfall condition from sowing to maturity was shown in Fig. 1.

Total N_2O emission expressed as kg N ha^{-1} included direct and indirect N_2O emissions which related to the N fertilizer rate. The calculation method of direct N_2O emissions (Cui et al., 2013) and indirect N_2O emissions including ammonia (NH_3) volatilization and nitrate (NO_3^-) leaching for spring maize is provided as below (Klein et al., 2006; Wu et al., 2014):

$$\text{Direct } N_2O \text{ emission} = 0.576 \times e^{(0.0049 \times \text{N rate})} \quad (9)$$

$$NH_3\ \textit{volatilization} = 0.24 \times \textit{N rate} + 1.30 \quad (10)$$

$$\text{N leaching} = 4.46 \times e^{(0.0094 \times \text{N rate})} \quad (11)$$

Indirect N_2O emission was estimated as 1% and 0.75% of NH_3 volatilization and N leaching.

Total GHG emissions during the entire life cycle of maize production, including CO_2, CH_4, and N_2O (CH_4 emission could be ignored in agroecosystem) consisted of three components, detailed equation is provided as below (Forster et al., 2007; Zhang et al.,

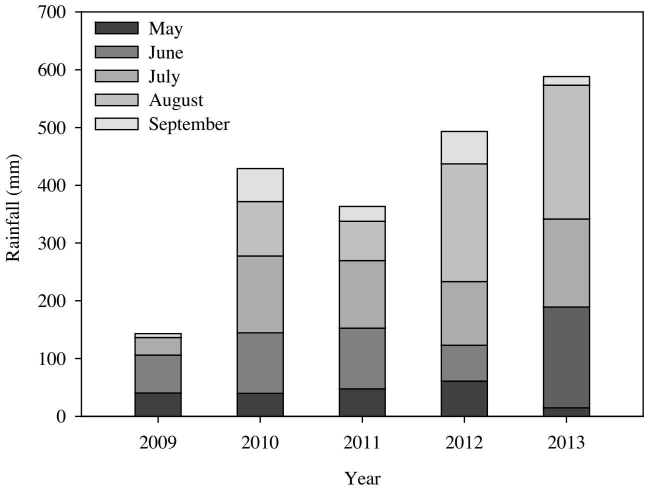

Fig. 1. Rainfall condition during maize growth season from 2009 to 2013 at ground weather station at Gongzhuling City.

2013):

$$GHG = (GHG_m + GHG_t) \times N\ rate + total\ N_2O \times \frac{44}{28} \times 298 + GHG_{others} \quad (12)$$

where GHG represents the total GHG emission calculated as CO_2 eq, GHG_m is the GHG emission factor of N product manufacturing and GHG_t is the GHG emission factor of N fertilizer transportation, GHG_{others} represents GHG emission of P and K fertilizer production and transportation (GHG_m and GHG_t were 8.21 and 0.09 kg CO_2 eq ha^{-1}; GHG_{others} for P and K were 0.79 and 0.55 kg CO_2 eq ha^{-1}). GHG emission intensity was expressed as kg CO_2 eq Mg^{-1} grain.

2.4. Maize potential yield and attainable yield simulation

The Hybrid Maize model was developed to simulated maize potential yield under non limiting or water-limited conditions with site-specific parameters including specific or historical weather data, planting, silking, maturity date and/or GDD values in specific years or long-term periods (Yang et al., 2004; Yang et al., 2006). The Hybrid Maize model combines the advantage of different maize modeling approaches and has been validated for the availability of yield potential estimation through field data for irrigated maize grown under optimal conditions (Grassini et al., 2009; Bai et al., 2006). Based on the conclusion of Evans (1993), potential yield (Yp) is defined as the maximum yield which could be reached by a crop in a given environment determined by simulation models with plausible physiology and agronomic assumptions. In our study, we defined Yw as potential yield (Yp) under water limited condition as benchmark for rainfed maize system, and 0.85 of Yp or Yw as the maximum yield when average farm yields could reach to the plateau under the growth condition and cultivar physiology limitation (van Ittersum et al., 2013). The Hybrid Maize model requires several parameters including planting date, climate condition (solar radiation, T_{max}, T_{min}, wind speed and precipitation), maturity date, plant density and water condition (Yw) to simulate the Yp or Yw. Yield gaps (Yg) was defined as the difference between 0.85 Yw and observed yield under EI or FP treatment.

2.5. Statistical analysis

The SAS System for Windows 8 was chosen for crop plant N uptake, AE_N, RE_N and PFP_N of two-way analysis of variance. A student test analysis was applied for maize grain yield and water productivity at significant level of P value <0.05.

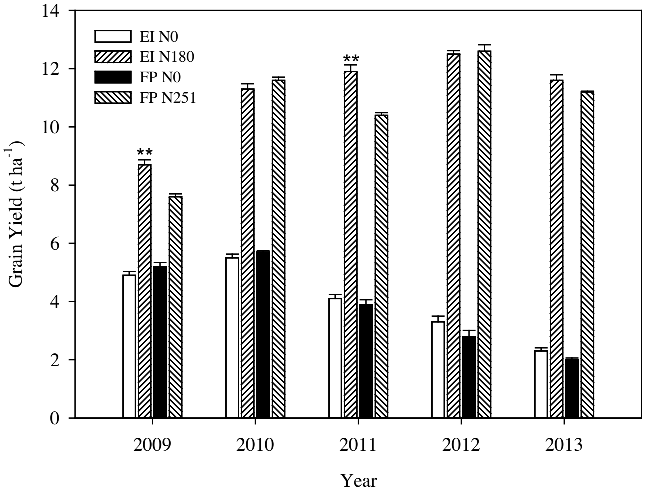

Fig. 2. Maize grain yield at Gongzhuling City from 2009 to 2013. Difference significance test of statistics at 0.05 level using SAS software, error bars indicate SE.

3. Results

3.1. Grain yield and yield gap

Grain yields (15.5% moisture content) of EI treatment in 2010, 2012 and 2013 did not show significant difference for FP treatment; however the grain yields of EI in 2009 and 2011 were significantly higher than FP treatment ($P < 0.01$; Fig. 2). Among the five-year grain yield results, the lowest grain yield happened in 2009, which was 8.7 t ha^{-1} for EI (N180) versus 7.6 t ha^{-1} for FP (N251) treatment; the highest grain yield happened in 2012, which was 12.5 t ha^{-1} for EI (N180) versus 12.6 t ha^{-1} for FP (N251) treatment. The average grain yield of EI (N180) and FP (N251) treatment were 11.8 t ha^{-1} and 11.4 t ha^{-1} respectively (exclusive of grain yield in 2009), which were less than the 12.0 t ha^{-1} of average irrigated maize grain yield in Nebraska and South East Asia (Setiyono et al., 2010), but higher than the 10.4 t ha^{-1} of average spring maize grain yield in northeast China (Zhang et al., 2012).

From the precipitation data collected from the weather station at Liufangzi County, the rainfall condition was 143.1 mm in 2009, which was approximately one fifth of the average of the other four years, resulting in the yield in 2009 was only 74% and 66% of the average yield of the next four years for EI and FP treatment, respectively (Fig. 1). A decrease of grain yield was observed from the N0 application in both EI and FP treatment during 2009–2013. Grain yield was 4.9 t ha^{-1} versus 5.2 t ha^{-1} in 2009; likewise, grain yield was 2.3 t ha^{-1} versus 2.0 t ha^{-1} in 2013 for EI and FP treatment. The declining soil mineral N availability is mainly the reason for the 50% decreased grain yield during 2009–2013.

The water-limited potential yields (Yw) of the EI treatment simulated by Hybrid Maize model ranged from 10.6 to 15.9 t ha^{-1} during 2009–2013 (Table 1). The lowest Yw was simulated at 10.6 t ha^{-1} in 2009, which was consistent with the lowest observed yield under both EI and FP treatment (Fig. 2). The whole average simulation Yw was 14.2 t ha^{-1}, with average yields of 11.2 t ha^{-1} and 10.7 t ha^{-1} in EI and FP treatment, which reached 78.3 and 74.8% of the simulated Yw, respectively.

Using 0.85Yw as an exploitable level, the calculations of 0.85Yw with a range of 9.0–13.5 t ha^{-1} from 2009 to 2013 were shown in Table 1. The mean Yg varied from 0.3 to 1.6 t ha^{-1} of EI 180 kg N ha^{-1} treatment, meanwhile, the mean Yg with a range of 0.5–3.1 t ha^{-1} was observed in FP 251 kg N ha^{-1} treatment (Table 1). This means that agricultural technology or nutrient management could be the limiting factor when the potential yield ceiling exists.

3.2. Nitrogen uptake and nitrogen use efficiency

Low plant N uptake occurred with the low grain yield in 2009 (Table 3). However, the equal plant N uptake amount level was observed between EI 180 kg N ha^{-1} and FP 251 kg N ha^{-1} treatment across five years. Due to the poor water condition, low grain yield in 2009 directly led to nearly 40% plant N uptake lost in the soil. The plant N uptake ranged from 173.8 to 187.3 kg ha^{-1} with the mean value of 181.8 kg ha^{-1} for EI (N180) treatment; and the plant N uptake ranged from 179.7 to 207.6 kg ha^{-1} with a mean value of 193.1 kg ha^{-1} for FP (N251) treatment from 2010 to 2013 (Table 3).

A new fertilizer recommendation approach, Nutrient Expert (NE) for hybrid maize was applied for fertilizer requirement evaluation in the EI treatment (Pampolino et al., 2012). Thus, AE_N in EI ranged from 20.6 to 51.8 kg kg^{-1} among the five years (Table 2) with an average of 39.7 kg kg^{-1}. RE_N in the EI treatment ranged from 28.8 to 88.4% with a mean value of 66.1%, and the scope of PFP_N in EI treatment ranged from 48.1 to 69.7 kg kg^{-1} with an

Table 1
Yield gap based on rain-fed condition between the ecological intensification (EI), and farmers' practice (FP) and the modeled yield in Jilin from 2009 to 2013.

	Observed yield (t ha^{-1})		Yw[a]	85% Yw[b]	Yield gap (0.85 Yw-EI)	Yield gap (0.85 Yw-FP)
	Ecological Intensification	Farmers' Practice				
2009	8.7	7.6	10.6	9.0	0.3	1.4
2010	11.3	11.6	14.2	12.1	0.8	0.5
2011	11.9	10.4	15.9	13.5	1.6	3.1
2012	12.5	12.6	15.7	13.3	0.8	0.7
2013	11.6	11.2	15.0	12.8	1.2	1.6

[a] Potential yield of maize based on rain-fed condition by using Hybrid Maize Model.
[b] 85% of Yw is the target for attainable yield.

average of 62.0 kg kg^{-1}. Correspondingly, AE_N in FP treatment ranged from 9.5 to 39.3 kg kg^{-1} with an average of 26.9 kg kg^{-1} which was 32.2% lower than in EI treatment. RE_N in FP treatment was observed within a range from 21.3 to 63.7% with an average of 50.4%; and a 23.8% decrease when compared to the RE_N in EI treatment. While PFP_N in the FP treatment varied from 30.3 to 50.2 kg kg^{-1} with a mean value of 42.5 kg kg^{-1}, which was 31.3% lower than PFP_N in EI treatment. The RE_{Na} was also calculated to evaluate the accumulated nitrogen uptake among five years with a range from 45.9 to 110.2% in EI treatment and from 31.6 to 84.0% in FP treatment, respectively. The average of RE_{Na} was 67.7% in EI treatment with a 24.3% increase compared to the average RE_{Na} value of 51.3% in FP treatment.

3.3. Estimated GHG emission

Compared to the FP treatment, the GHG emission for EI decreased from 3629 to 2547 kg CO_2 eq ha^{-1} (Table 4). Calculated from GHG emission and grain production, GHG intensity would be decreased by 34%, from 350 kg CO_2 eq Mg^{-1} grain in FP treatment to 231 kg CO_2 eq Mg^{-1} grain in EI treatment. The overuse of N fertilizer in FP treatment has resulted in high direct and indirect N_2O emissions which were 1.97 and 0.97 kg N ha^{-1}, respectively (Table 4). In contrast to the FP treatment, EI has lower direct and indirect N_2O emissions which were 1.39 and 0.63 kg N ha^{-1}, respectively. According to the results from GHG emission components, fertilizer N overuse could account for a large proportion of total GHG emission (58% for EI and 57% for FP treatment). However, GHG emission caused by N fertilizer use in FP treatment was 31% higher than in EI treatment.

Table 2
Effects of the ecological intensification on recovery efficiency (RE_N), accumulated recovery efficiency (RE_{Na}), agronomic N use efficiency (AE_N) and partial factor productivity of applied N (PFP_N) in maize from 2009 to 2013.

Year	Cultivation systems	RE_N (%)	RE_{Na} (%)	AE_N (kg kg^{-1})	PFP_N (kg kg^{-1})
2009	EI	28.3a		20.6a	48.1a
	FP	21.3a		9.5b	30.3b
2010	EI	63.3a	45.9a	32.0a	62.7a
	FP	41.9b	31.6b	23.0b	46.1b
2011	EI	70.9a	54.2a	43.0a	64.8a
	FP	63.7b	42.3b	26.1b	41.6b
2012	EI	79.7a	60.6a	51.1a	69.7a
	FP	62.1a	47.2b	39.3b	50.2b
2013	EI	88.4a	110.2a	51.8a	64.6a
	FP	63.0b	84.0b	36.6b	44.5b

Letters indicate significance analysis by Tukey-HSD test was used for multiple comparisons of the means between EI and FP treatment.

3.4. Nitrogen balance and soil N loss

In order to decrease the soil N loss to the environment, the calculation of apparent N loss was evaluated in Table 3. The results showed that crop N uptake was 110.3 kg ha^{-1} in EI treatment when the experiment was initiated from 2009. The increasing crop N uptake was observed in the following four years with an average of 181.8 kg ha^{-1} which was contributed by the low N fertilizer input and high N use efficiency. For the FP treatment, the mean crop N uptake value was 193.1 kg ha^{-1}, thus, the excessive fertilizer N input was highly associated with these results. Considering the difference between total N input and the crop N uptake, residual soil N_{min} was measured in EI and FP treatment during 2009–2013. The high residual soil N_{min} (475.7 kg ha^{-1}) observed in EI treatment in 2009 was related to the specific drought condition, which resulted in low soil N mineralization activity and rate. However, when the weather conditions went back to normal, especially the precipitation, the residual soil N_{min} was 57.6, 96.7, 83.2 and 51.8 kg ha^{-1} with a mean value of 72.3 kg ha^{-1} in EI treatment; while, the residual soil N_{min} was 51.7, 199.8, 203.2 and 197.1 kg ha^{-1} with an average of 163.0 kg ha^{-1} in FP treatment from 2010 to 2013.

Given to the calculated N balance among five years, apparent N loss in EI (180 kg ha^{-1}) was lower than in FP (251 kg ha^{-1}). Nevertheless, little difference in crop N uptake between EI (837.7 kg ha^{-1}) and FP (885.9 kg ha^{-1}) but substantially lower soil residual N_{min} was observed in EI (765.4 kg ha^{-1}) than in FP (1224.1 kg ha^{-1}) in Table 3, indicating high environmental costs were caused by exceeding optimum N rates.

4. Discussion

4.1. Improved practices of ecological intensification management

From 2009–2013, five seasons of spring maize were managed using a split-plot design with management system as a whole plot factor consisting of two treatments (EI or FP), and N fertilization as the sub-plot factor with two levels (N or N0). The highest grain yield attained in EI treatment (N180) was 12.5 t ha^{-1} with an average value of 11.8 t ha^{-1} (Fig. 2). On average, the mean grain yield in FP treatment (N251) was 11.4 t ha^{-1}, and the mean grain yield of spring maize in northeast China was 11.3 t ha^{-1} (Xu et al., 2014). According to Meng et al. (2013), based on the weather data, sowing and harvest dates, and density, the simulated average potential yield in 14 sites located in northeast China by the Hybrid Maize model was 15.9 t ha^{-1}. Meanwhile, the highest recorded maize yield was 15.8 t ha^{-1} in northeast China with extensive inputs regardless of environmental costs (Meng et al., 2013). The mean grain yield of irrigated maize in Nebraska was 11.0 t ha^{-1}, while the experimental-field grain yield of irrigated maize was 13.8 t ha^{-1} (Setiyono et al., 2010). Attainable grain yield in the EI treatment (N180) has reached 78.0% and 92.6% of Yw and 0.85Yw

Table 3
Calculated apparent N losses between the ecological intensification (EI), and farmers' practice (FP) in Jilin from 2009 to 2013.

		Input (kg ha^{-1})			Output (kg ha^{-1})		
Year	Treatment	N application	Initial N_{min}	Net N mineralization	Crop N uptake	Residual N_{min}	Apparent N loss
2009	EI N0	0	52	132.5	59.3a	125.2	0
	FP N0	0	52	110.1	59.8a	102.3	0
	EI N180	180	52	132.5	110.3b	475.7	−221.5
	FP N251	251	52	110.1	113.3b	572.3	−272.5
2010	EI N0	0	125.2	0	73.3a	48.6	0
	FP N0	0	102.3	17.2	93.2a	26.3	0
	EI N180	180	475.7	0	187.3b	57.6	410.8
	FP N251	251	572.3	17.2	198.2b	51.7	590.6
2011	EI N0	0	48.6	49.0	46.3a	51.3	0
	FP N0	0	26.3	68.2	47.8a	46.7	0
	EI N180	180	57.6	49.0	173.8b	96.7	−28.9
	FP N251	251	51.7	68.2	207.6b	199.8	−36.5
2012	EI N0	0	51.3	21.5	39.0a	33.8	0
	FP N0	0	46.7	32.4	31.3a	47.8	0
	EI N180	180	96.7	21.5	182.4b	83.2	32.6
	FP N251	251	199.8	32.4	187.1b	203.2	92.9
2013	EI N0	0	33.8	43.8	24.8a	52.8	0
	FP N0	0	47.8	18.8	21.6a	45.0	0
	EI N180	180	83.2	43.8	183.9b	51.8	71.3
	FP N251	251	203.2	18.8	179.7b	197.1	96.2
5-year	EI N0	0	310.9	246.8	242.7a	311.7	0
	FP N0	0	275.1	246.7	253.7a	268.1	0
	EI N180	900	765.2	246.8	837.7b	765.4	309.0
	FP N251	1255	1079	246.7	885.9b	1224.1	470.7

Note: Initial N_{min} was measured as residual NO_3—N and NH_4—N in 0–90 cm soil depth before sowing; net N_{min} was calculated by the difference method under N0 plot described by Eq. (8); letters indicate significance analysis by Tukey-HSD test was used for multiple comparisons of the means between different N application treatments.

(Table 1), while farmers achieved about 74.8% and 88.4% of Yw and 0.85Yw, respectively. Compared to the yield gap in Nebraska, where the actual yields were within 80–90% of simulated yield potential, the yield gap in this study for the EI treatment (N180) was getting closer to Yw than the FP treatment (N251). These results indicated that the EI treatment has advantages of high maize productivity achievement through optimal management practices.

The combined practices including N rates, planting date, plant density, and hybrid variety selection of the EI treatment were recommended by Nutrient Expert® (NE) Recommendation Method depending on soil indigenous nutrient supply, crop yield response and crop nutrient uptake (Xu et al., 2014). Multiple-splitting time of fertilization has more advantages in nutrient mobilization and transportation compared to one-time basal fertilization, research results indicated that developing seed began to mobilize and utilize N transferred from leaves and straw when maize moved into the reproductive stage (He et al., 2011), and about 60% grain N was transferred from leaves and straw, while only 40% grain N came from the environment during grain filling stage (Hay et al., 1953; Chun et al., 2005).

Maize density under simulation yield potential or highest yield record condition was between 70,000 and 100, 000 plants ha^{-1}, and maize density in farmers' field in China was around 50,000 to 60,000 plant ha^{-1} in most cases (Chen et al., 2012; Meng et al., 2013), in contrast with 75,000 to 82,500 plant ha^{-1} plant density in United States. Higher plant density increased above-ground biomass with applied N, especially with side-dress N application; whereas maximum grain yield could reliably implement at the optimum plant density considering the influences of light and nutrition competition for a specific genotype and environment (Grassini and Cassman, 2012; Tokatlidis and Koutroubas, 2004). In terms of different climate and field management types, average estimated 0.85 Yw (water-limited) in northeast China was 21.4% lower than the average potential yield in Nebraska, thus the total water supply requirement should be evaluated with climatic and realistic field management. These results indicated that narrowing of the yield gap between observed yield and yield potential (no water-limitation) could be achieved by using an irrigation strategy (drip irrigation and/or pivot irrigation plus conservation tillage).

4.2. Nitrogen uptake and loss

As expected, plant N uptake in the EI treatment (N180) with 181.8 kg ha^{-1} was equal to FP treatment (N251) with 193.1 kg ha^{-1} (Table 3) which indicated soil plus fertilizer N have been enough for crop N demand in the EI treatment. Similar results were presented by Ciampitti and Vyn (2011), no N deficiency symptoms

Table 4
Direct, indirect, total N_2O emissions, and GHG emission from N fertilizer use, N fertilizer production and others sources between ecological intensification (EI) and farmers' practice (FP).

	N_2O emissions (kg N ha^{-1})			GHG emissions (kg CO_2 eq ha^{-1})				GHG emission intensity (kg CO_2 eq Mg^{-1} grain)
	Direct	Indirect	Total	N fertilizer use	N fertilizer production	Others	Total	5-year average value
EI	1.39	0.63	2.02	945	1477	125	2547	231
FP	1.97	0.97	2.94	1376	2060	192	3629	350

was observed at medium N rate (N165). According to Xu et al. (2014), the average plant N uptake across 418 sites was 201.8 kg ha^{-1} in spring maize in seven provinces from 2010 to 2012. Either average plant N uptake of EI 180 kg N ha^{-1} or FP 251 kg N ha^{-1} treatment was less than 232.2 kg ha^{-1} of average plant N uptake across 2341 field measurements in Nebraska but much higher than 174.6 kg/ha of average plant N uptake in northeast China (Setiyono et al., 2010). Ciampitti and Vyn (2012) presented the statistical results of N uptake and grain yield across around 3000 individual points, studies from 1991 to 2011 afterwards with grain yield of 9.0 t ha^{-1} and plant N uptake of 170 kg ha^{-1} at an average plant density of 71,000 plants per ha. There are some possibilities of improving maize plant N uptake amount in the future by maize hybrid variety (high tolerance to N deficiency) and high plant density selection in China (Setiyono et al., 2010).

In order to reduce the N loss to environment, N use efficiency should be improved properly. A combination of three parameters of AE_N, RE_N and PFP_N were adopted to understand the N uptake efficiency more precisely. In our study, the mean 39.7 kg kg^{-1} AE_N in EI treatment (Table 2) was compared to the range from 0 to 60 kg kg^{-1} of previously reported by Ladha et al. (2005), but much higher than the mean AE_N value of 24.4 kg kg^{-1} reported by Uribelarrea et al. (2007). In agreement with Boomsma et al. (2009) that, the highest AE_N was gained at medium N rate (N165) with either high plant density (104,000 plant ha^{-1}) or the intermediate plant density (79,000 plant ha^{-1}). Even the average AE_N in FP treatment with low plant density (50,000 plant ha^{-1}) and high N rate (251 kg ha^{-1}) also reached to 26.9 kg kg^{-1}; moreover, Dobermann and Cassman (2004) reported that AE_N declined to 23.0 kg kg^{-1} when N fertilizer rates exceed 200 kg ha^{-1}. As AE_N itself is not enough to understand the effects of field management on crop N uptake dynamics being comprised both soil and plant processes, RE_N with advances in connecting to plant N uptake efficiency is more adaptive in our study. The mean RE_N of 37.0% was observed in North-Central U.S. (Cassman et al., 2002). Researchers insisted that RE_N should range between zero and the unit for its meaningful in agronomy and biology perspectives. And according to substantial data observation, RE_N dropped from period of 1940–1990 (53%) as compared to the period of 1991–2011 afterwards (44%) which was resulted from improved N application (Ciampitti and Vyn 2012). The average RE_N in EI and FP treatment were 66.1 and 42.5% (Table 2), suggesting that soil and fertilizer N can be utilized more effective under medium N rate (N180) in northeast spring maize cropping system areas, despite the fact that grain yield in EI treatment was equal to FP treatment (Fig. 2). PFP_N was simply termed as the ratio between grain yield and N applied, the EI treatment resulted in a PFP_N value of 62.2 kg kg^{-1}, while the PFP_N was 50.4 kg kg^{-1} in the FP treatment (apparently 12 units lower). PFP_N in EI treatment in our study exceeds 5 units as compared to this value recently reported by Chen et al. (2011), but below the average PFP_N value observed in high-yielding irrigated maize system (73 kg kg^{-1}) by Grassini and Cassman (2012).

Since the improved components of nitrogen use efficiency including AE_N, RE_N and PFP_N indicated medium fertilizer N rate could promote plant N high-efficiency utilization, which means less residual soil N_{min} should be observed in EI treatment compared to FP treatment (Table 3). The equal crop N uptake between EI and FP treatments showed that optimum fertilizer N rate (N180), plus split-application at critical growth stage, could satisfy the crop nutrient demand and promote the net N mineralization (Table 3). The calculated residual N_{min} in EI treatment through five years was 37.5% lower than this value in FP treatment, and the apparent N loss was 34.3% lower in EI treatment when compared with FP. Numerous research results have attributed excessive N loss to the environment (including freshwater and air) to high quantity of fertilizer N application beyond the crop requirement (Zhao et al., 2006; Ju et al., 2009; Cui et al., 2008a). The concentrated-rainfall during the spring maize growth period (Fig. 1) could be the reason for apparent N loss besides the excessive N fertilizer application.

GHG emissions have been a great part of N loss, farmers' practices used in current intensive maize system have resulted in high GHG emission intensity which was 350 kg CO_2 eq Mg^{-1} grain with high fertilizer N input (251 kg ha^{-1}). By contrast, GHG emission intensity in the EI treatment was 231 kg CO_2 eq Mg^{-1} grain with 180 kg ha^{-1} (Table 4). According to the results of Grassini and Cassman (2012), GHG emission intensity in Nebraska, USA was 231 kg CO_2 eq Mg^{-1} grain with 183 kg N ha^{-1} which was equal to the results in EI treatment and 34 lower than the 350 kg CO_2 eq Mg^{-1} for FP treatment. These results showed that the EI treatment could efficiently decrease 982 kg CO_2 eq ha^{-1} on GHG emission in contrast to FP treatment (Table 4). Thus based on the spring maize cultivated area in northeast China (8.0×10^6 ha), reduced GHG emission could be estimated at 7.8 Tg CO_2 yr^{-1} with improved N management practices.

5. Conclusion

In our study, optimized planting density, fertilizer N rate and application timing were implemented to improve corn grain yield and reduce the negative impacts on the environment during 2009–2013 in Jilin province. Compared with FP, the EI treatment could maintain crop grain yield, improve nutrient efficiency and decrease GHG emission. The ideas of EI describe a tremendous blueprint between intensification and sustainability, and could be a natural link of biological and agronomic process. Any optimum field management practices including plant density, fertilizer N rate and timing pattern based on ecological intensification concepts provide one promising alternative for spring maize cropping system management in northeast China.

Acknowledgments

This research was supported by the Global Maize Project (GM), International Plant Nutrition Institute (IPNI), and CAAS-IPNI Joint Lab for Plant Nutrition Innovation Research. We would like to thank the scientists from Academy of Agricultural Sciences of Jilin. And we are also grateful for the patience and help offered by the farmers in our study.

References

Bai, J.S., Chen, X.P., Dobermann, A., Yang, H.S., Cassman, K.G., Zhang, F.S., 2006. Evaluation of NASA satellite- and model-derived weather data for simulation of maize yield potential in China. Agron. J. 102, 9–16.

Bishwajit, G., Sarker, S., Kpoghomou, M.-A., Gao, H., Jun, L., Yin, D., Ghosh, S., 2013. Self-sufficiency in rice and food security: a South Asian perspective. Agric. Food Secur. 2, 1–6.

Boomsma, C.R., Santini, J.B., Tollenarr, M., Vyn, T.J., 2009. Maize per-plant and canopy-level morpho-physiological response to the simultaneous stresses of intense crowding and low nitrogen availability. Agron. J. 101, 1426–1452.

Cassman, K.G., Dobrmann, A., Walters, D.T., 2002. Agroecosystems nitrogen-use efficiency, and nitrogen management. Ambio 31, 132–140.

Cassman, K.G., 1999. Ecological intensification of cereal production systems: yield potential soil quality, and precision agriculture. Proc. Natl. Acad. Sci. U. S. A. 96, 5952–5959.

Chen, X.P., Cui, Z.L., Vitousek, P.M., Cassman, K.G., Matson, P.A., Bai, J.S., Meng, Q.F., Hou, P., Yue, S.C., Romheld, V., Zhang, F.S., 2011. Integrated soil–crop system management for food security. Proc. Natl. Acad. Sci. U. S. A. 108, 6399–6404.

Chen, G.P., Gao, J.L., Zhao, M., Dong, S.T., Li, S.K., Yang, Q.F., Liu, Y.H., Wang, L.C., Xue, J. Q., Liu, J.G., Li, C.H., Wang, Y.H., Wang, Y.D., Song, H.X., Zhao, J.R., 2012. Distribution, yield structure, and key cultural techniques of maize super-high yield plots in recent years. Acta Agron. Sin. 38, 80–85 (in Chinese with English abstract).

Chen, X.P., Cui, Z.L., Fan, M.S., Vitousek, P., Zhao, M., Ma, W.Q., Wang, Z.L., Zhang, W.J., Yan, X.Y., Yang, J.C., Deng, X.P., Gao, Q., Zhang, Q., Guo, S.W., Ren, J., Li, S.Q., Ye, Y. Y., Wang, Z.H., Huang, J.L., Tang, Q.Y., Sun, Y.X., Peng, X.L., Zhang, J.W., He, M.R., Zhu, Y.J., Xue, J.Q., Wang, G.L., Wu, L., An, N., Wu, L.Q., Ma, L., Zhang, W.F., Zhang, F.S., 2014. Producing more grain with lower environmental costs. Nature 514, 486–489.

Editorial Board of Agriculture Yearbook of China. In: China Agriculture Yearbook (Ed.), China Agriculture Press, Beijing (in Chinese).

Christopher, M.C., Tilman, D., 2008. Loss of plant species after chronic low-level nitrogen deposition to prairie grasslands. Nature 451, 712–715.

Chuan, L.M., He, P., Pampolino, M.F., Johnston, A.M., Jin, J.Y., Xu, X.P., Zhao, S.C., Qiu, S.J., Zhou, W., 2013. Estimating a scientific basis for fertilizer recommendations for wheat in China: yield response and agronomic efficiency. Field Crops Res. 140, 1–8.

Chun, L., Chen, F.J., Zhang, F.S., Mi, G.H., 2005. Root growth: nitrogen uptake and yield formation of hybrid maize with different N efficiency. Plant Nutr. Fertil. Sci. 11, 615–619.

Ciampitti, I.A., Vyn, T.J., 2011. A comprehensive study of plant density consequences on nitrogen uptake dynamics of maize plants from vegetative to reproductive stages. Field Crops Res. 121, 2–18.

Ciampitti, I.A., Vyn, T.J., 2012. Physiological perspectives of charges over time in maize yield dependency on nitrogen uptake and associated nitrogen efficiencies: a review. Field Crops Res. 133, 48–67.

Cui, Z.L., Chen, X.P., Zhang, F.S., Miao, Y.X., Li, J.L., 2008a. On-farm evaluation of the improved soil N_{min}-based nitrogen management for summer maize in North China Plain. Agron. J. 100, 517–525.

Cui, Z.L., Miao, Y.X., Zhang, F.S., Chen, X.P., 2008b. Soil nitrate-N levels required for high yield maize production in the North China Plain. Nutr. Cycl. Agroecosyst. 82, 187–196.

Cui, Z.L., Zhang, F.S., Chen, X.P., Miao, Y.X., Li, J.L., Shi, L.W., Xu, J.W., Ye, Y.L., Liu, C.S., Yang, Z.P., Zhang, Q., Huang, S.M., Bao, D.J., 2008c. On-farm estimation of indigenous nitrogen supply for site-specific nitrogen management in the North China plain. Nutr. Cycl. Agroecosyst. 81, 37–47.

Cui, Z.L., Chen, X.P., Zhang, F.S., 2010. Current nitrogen management status and measures to improve the intensive wheat–maize system in China. Ambio 39, 376–384.

Cui, Z.L., Yue, S.C., Wang, G.L., Meng, Q.F., Wu, L., Yang, Z.P., Zhang, Q., Li, S.Q., Zhang, F.S., Chen, X.P., 2013. Closing the yield gap could reduce projected greenhouse gas emissions: a case study of maize production in China. Global Change Biol. 19, 2467–2477.

Davidson, E.A., 2009. The contribution of manure and fertilizer nitrogen to atmospheric nitrous oxide since 1860. Nat. Geosci. 2, 659–662.

Dension, R.F., 2012. Darwinian Agriculture: How Understanding Evolution Can Improve Agriculture. Princeton University Press, Princeton.

Diaz, R.J., Rosenberg, R., 2008. Spreading dead zones and consequences for marine ecosystems. Science 321, 926–929.

Dobermann, A., Cassman, K.G., et al., 2004. Enviromental dimension of fertilizer N: what can be done to increase nitrogen use efficiency and ensure global food security? In: Mosier, A.R. (Ed.), Agriculture and the Nitrogen Cycle: Assessing the Impacts of Fertilizer Use on Food Production and the Environment. SCOPE 65. Island Press, Washington, D.C.

Dobermann, A., Cassman, K.G., 2005. Cereal area and nitrogen use efficiency are drivers of future nitrogen fertilizer consumption. Sci. Chin. Ser. C 48, 745–758.

Dobermann, A., 2005. Nitrogen use efficiency state of the art. Paper of the IFA International Workshop on Enhanced Efficiency Fertilizers, Frankfurt, Germany.

Evans, L.T., 1993. Crop Evolution, Adaptation, and Yield. Cambridge University Press, Cambridge, UK.

Fan, M.S., Christie, P., Zhang, W.F., Zhang, F.S., 2010. Crop production, fertilizer use and soil quality in China. In: Lal, R., Stewart, B.A. (Eds.), Advances in Soil Science: Food Security and Soil Quality. CRC Press, Talyor & Francis Group, Boca Raton, London, New York.

Fan, M.S., Shen, J.B., Yuan, L.X., Jiang, R.F., Chen, X.P., Davies, W.J., Zhang, F.S., 2012. Improving crop productivity and resource use efficiency to ensure food security and environmental quality in China. J. Exp. Bot. 63, 13–24.

Flavell, R., 2010. Knowledge and technologies for sustainable intensification of food production. New Biotechnol. 27, 505–516.

Forster, P., Ramaswamy, V., Artaxo, P., Berntsen, T., Betts, R., Fahey, D.W., Haywood, J., Lean, J., Lowe, D.C., Myhre, G., Nganga, J., Prinn, R., Raga, G., Schulz, M., Dorland, R.V., 2007. Changes in atmospheric constituents and in radiative forcing in Climate Change. In: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., Miller, H.L. (Eds.), The Physical Science Basis Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.

Gehring, C., de Moura, E.G., Santos, R.R.S., Aguiar, A.C.F., de Sousa, A.M.B., Boddey, R.M., 2013. Ecological intensification of rice production in the lowlands of Amzaonia—options for smallholder rice producers. Eur. J. Agron. 46, 25–33.

Grassini, P., Cassman, K.G., 2012. High-yield maize with large net energy yield and small global warming intensity. Proc. Natl. Acad. Sci. U. S. A. 109, 1074–1079.

Grassini, P., Yang, H.S., Cassman, K.G., 2009. Limits to maize productivity in Western Corn-belt: a simulation analysis for fully irrigated and rainfed conditions. Agric. For. Meteorol. 149, 1254–1265.

Guo, J.H., Liu, X.J., Zhang, Y., Shen, J.L., Han, W.X., Zhang, W.F., Christie, P., Goulding, K.W.T., Vitousek, P.M., Zhang, F.S., 2010. Significant acidification in major Chinese croplands. Science 327, 1008–1010.

Hay, R.E., Earley, E.B., Deturk, E.E., 1953. Concentration and translocation of nitrogen compounds in the corn plant (*Zea mays*) during grain development. Plant Physiol. 28, 606–621.

He, P., Li, S.T., Jin, J.Y., Wang, H.T., Li, C.J., Wang, Y.L., Cui, R.Z., 2009. Performance of an optimized nutrient management system for double-cropped wheat-maize rotations in North-central China. Agron. J. 101, 1489–1496.

He, C.E., Wang, X., Liu, X., Fangmeier, A., Christie, P., Zhang, F., 2011. Total nitrogen deposition at key growing stages of maize and wheat as affected by pot surface area and crop variety. Plant Soil 339, 137–145.

Ju, X.T., Xing, G.X., Chen, X.P., Zhang, S.L., Zhang, L.J., Liu, X.J., Cui, Z.L., Yin, B., Christie, P., Zhu, Z.L., 2009. Reducing environmental risk by improving N management in intensive Chinese agricultural systems. Proc. Natl. Acad. Sci. U. S. A. 106, 14908–14913.

Klein, C.D., Novoa, R.S.A., Ogle, S., Smith, K.A., Rochette, P., Wirth, T.C., McConkey, B.G., Mosier, A., Rypdal, K., 2006. IPCC Guidelines for National Greenhouse Gas Inventories. Chapter 11: N_2O Emissions from Managed Soils, and CO_2 Emissions from Lime and Urea Application. http://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/4_Volume4/V4_11_Ch11_N2O&CO2.pdf.

Ladha, J.K., Pathak, H., Krupnik, J., Six, J., van Kessel, C., 2005. Efficiency of fertilizer nitrogen in cereal production: retrospects and prospects. In: Donald, L.S. (Ed.), Advances in Agronomy. Academic Press, San Diego, CA, pp. 85–156.

Li, H., Zhang, W., Zhang, F., Du, F., Li, L., 2010. Chemical fertilizer use and efficiency change of main grain crops in China. Plant Nutr. Fertil. Sci. 16, 1136–1143.

Meng, Q.F., Hou, P., Wu, L., Chen, X.P., Cui, Z.L., Zhang, F.S., 2013. Understanding production potentials and yield gaps in intensive maize production in China. Field Crops Res. 143, 91–97.

Pampolino, M.F., Witt, C., Pasuquin, J.M., Johnston, A., Fisher, M.J., 2012. Development approach and evaluation of the nutrient Expert software for nutrient management in cereal crops. Comput. Electron. Agric. 88, 103–110.

Rusinamhodzi, L., Corbeels, M., Nyamangara, J., Giller, K.E., 2012. Maize–grain legume intercropping is an attractive option for ecological intensification that reduces climatic risk for smallholder farmers in central Mozambique. Field Crops Res. 136, 12–22.

Setiyono, T.D., Walter, D.T., Cassman, K.G., Witt, C., Dobermann, A., 2010. Estimating maize nutrient uptake requirements. Field Crops Res. 118, 158–168.

Tokatlidis, I.S., Koutroubas, S.D., 2004. A review of maize hybrids' dependence on high plant population and its implication for crop yield stability. Field Crops Res. 88, 103–114.

Uribelarrea, M., Moose, S.P., Below, F.E., 2007. Divergent selection for grain protein affects nitrogen use in maize hybrids. Field Crops Res. 100, 82–97.

van Ittersum, M.K., Cassman, K.G., Grassini, P., Wolf, J., Tittonell, P., Hochman, Z., 2013. Yield gap analysis with local to global relevance—a review. Field Crops Res. 143, 4–17.

Wu, L., Chen, X.P., Cui, Z.L., Zhang, W.F., Zhang, F.S., 2014. Establishing a regional nitrogen management approach to mitigate greenhouse gas emission intensity from intensive smallholder maize production. PLoS One 9, e98491. doi:http://dx.doi.org/10.1371/journal.pone.0098481.g001.

Xu, X.P., He, P., Qiu, S.J., Pampolino, M.F., Zhao, S.C., Johnston, A.M., Zhou, W., 2014. Estimating a new approach of fertilizer recommendation across small-holder farms in China. Field Crops Res. 163, 10–17.

Yang, H.S., Dobermann, A., Lindquist, J.L., Walters, D.T., Arkebauer, T.J., 2004. Hybrid-maize-a maize simulation model that combines two crop modeling approaches. Field Crops Res. 87, 131–154.

Yang, H.S., Dobermann, A., Cassman, K.G., Walters, D.T., 2006. Features applications, and limitations of the hybrid-maize simulation model. Agron. J. 98, 737–748.

Zhang, F.S., Wang, J.Q., Zhang, W.F., Cui, Z.L., Ma, W.Q., Chen, X.P., Jiang, R.F., 2008. Situation and counter measures of nutrient utilization efficiency for major cereal crops in China. Acta Pedologica Sinica 45, 915–924.

Zhang, F.S., Cui, Z.L., Fan, M.S., Zhang, W.F., Chen, X.P., Jiang, R.F., 2011. Integrated soil–crop system management: reducing environmental risk while increasing crop productivity and improving nutrient use efficiency in China. J. Environ. Qual. 40, 1051–1057.

Zhang, W.F., Dou, Z.X., He, P., Ju, X.T., Powlson, D., Chadwick, D., Norse, D., Lu, Y.L., Zhang, Y., Wu, L., Chen, X.P., Cassman, K.G., Zhang, F.S., 2013. New technologies reduce greenhouse gas emissions from nitrogenous fertilizer in China. Proc. Natl. Acad. Sci. U. S. A. 110, 8375–8380.

Zhao, R.F., Chen, X.P., Zhang, F.S., Zhang, H.L., Schroder, J., Romheld, V., 2006. Fertilization and nitrogen balance in a wheat–maize rotation system in North China. Agron. J. 98, 938–945.

Zhang, Y., Hou, P., Gao, Q., Chen, X.P., Zhang, F.S., Cui, Z.L., 2012. On-farm estimation of nutrient requirements for spring corn in north China. Agron. J. 104, 1436–1442.