



## Narrowing yield gaps and increasing nutrient use efficiencies using the Nutrient Expert system for maize in Northeast China



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### ABSTRACT

A science-based, reliable, and feasible fertilizer recommendation method is required to respond to the low nutrient use efficiency caused by inappropriate fertilization practices. Soil test-based fertilizer recommendations are difficult to use for smallholder farms because of constraints such as access, cost and timeliness in multiple cropping systems. In this study, we combined on-farm experiments from 2012 to 2014 in 20 farmers' fields on spring maize in Northeast China with a simulation model (Hybrid Maize model), to test the continual performance in agronomic, economic and environmental aspects of the Nutrient Expert for Hybrid Maize decision support system. Six treatments were set as follows: Nutrient Expert (NE), farmers' practice (FP), soil testing (OPTS) and nitrogen (N), phosphorus (P), and potassium (K) omission treatments based on NE. We estimated yield gaps as the difference between simulated yields with the Hybrid Maize model and measured yields; calculated economic benefit and nutrient use efficiency; and estimated greenhouse gas emissions using published equations approximating nitrous oxide emissions as a function of N fertilizer rate. On average, the NE, FP, and OPTS treatments attained yields of 80%, 74%, and 77% of the potential yield, respectively. The exploitable yield gap between the NE and FP treatments was  $0.9 \text{ t ha}^{-1}$ , and between the NE and OPTS treatments was  $0.5 \text{ t ha}^{-1}$ . On average, the NE treatment increased the gross return above fertilizer cost (GRF) by US\$303 and US\$167 compared with the FP and OPTS treatments across all sites, respectively, in which about 91% and 98% of increase GRF was attributed increase in grain yield rather than reduction in fertilizer cost. There were slightly higher nutrient use efficiencies under the NE treatment than under the OPTS treatment. Relative to the FP treatment, however, on average, the NE treatment increased recovery efficiency of N, P, and K by percentage point of 12, 15, and 10, respectively. Agronomic efficiency of N, P, and K were increased by 6, 35, and  $10 \text{ kg kg}^{-1}$ , respectively. Finally, partial factor productivity increased by  $14 \text{ kg kg}^{-1}$  for N and  $45 \text{ kg kg}^{-1}$  for P while decreased by  $29 \text{ kg kg}^{-1}$  for K. Furthermore, the calculated soil inorganic N at harvest of maize crop, total greenhouse gas (GHG,  $\text{kg CO}_2 \text{ eq ha}^{-1}$ ) emissions, and GHG emission intensity ( $\text{kg CO}_2 \text{ eq t}^{-1}$  grain) were 42%, 17%, and 23% lower in the NE treatment than the FP treatment, respectively. We conclude that the Nutrient Expert for Hybrid Maize system has the potential to close existing yield gaps in the spring maize production systems of Northeast China by improving yield, nutrient use efficiency, and profitability with low environmental pollution.

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**Abbreviations:** AE, agronomic efficiency; FP, farmers' fertilizer practice; GHG, greenhouse gas; GRF, gross return above fertilizer cost; NE, Nutrient Expert; OPTS, soil testing; PFP, partial factor productivity; RE, recovery efficiency; TFC, total fertilizer cost.

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## 1. Introduction

Maize (*Zea mays* L.) production plays an important role in ensuring food safety and stabilizing the grain market in China. High-yield cultivars, high fertilizer addition rates, effective pesticides and integrated crop management have helped to increase maize yield in recent decades (Chen et al., 2011; Li et al., 2011). However, grain production must continue to increase to match the expansion of the population (Zhang, 2011). Understanding potential yield and narrowing the yield gap in current intensive maize production is essential for increasing yield to meet future food requirements.

Exploring the yield gap between potential yield and farmers' yield is one of the key components for food security (Lv et al., 2015). The potential yield commonly refers to water-unlimited potential yield (in irrigated systems) and water-limited potential yield (in rainfed conditions) (Evans and Fischer, 1999; Lobell et al., 2009). Maize potential yield can be estimated using historical weather data with crop models, such as Hybrid-Maize model (Yang et al., 2004; Bai et al., 2010; Meng et al., 2013). The yield gaps can be measured in various ways, including model, experiment, and farmer-based yield gap, etc. (Lobell et al., 2009). Numerous soil and crop management methods have been adopted that aim to increase maize yield and close the yield gap. Examples include optimizing the N rate based on testing soil  $\text{NO}_3\text{-N}$  content in the root layer (Chen et al., 2010), the combination of organic resources and mineral fertilizer application (Chivenge et al., 2011), site-specific nutrient management (Pasquin et al., 2014), and fertilizer recommendation based on soil testing, yield targets and crop responses (He et al., 2009).

Nutrient management is considered to be one of the most important factors for increasing yield and narrowing the yield gap. However, long-term sustainable high crop yields require integrated nutrient management practices because excessive fertilizer application has become a common issue in China over recent years, particularly for nitrogen (N) and phosphorus (P) fertilizer (He et al., 2009; Cui et al., 2010). This overuse of N and P fertilizers does lead to further yield improvements, instead causing nutrient accumulation in the soil, low nutrient use efficiency and environmental pollution, such as greenhouse gas (GHG) emissions, water pollution and nutrient leaching (Ju et al., 2009; Le et al., 2010; Gao et al., 2012; Xu et al., 2015; Le et al., 2010; Gao et al., 2012; Xu et al., 2015). Therefore, improvements to fertilizer use recommendations are necessary to promote effective integrated management.

As one of the three "golden corn belts" of the world, Northeast China is an important maize production region, and plays a unique role in maintaining crop yield. Maize planting area and yield in this region account for 31% and 35% of the total for China, respectively (China Agriculture Yearbook, 2014). However, nutrient management in the Northeast China still faces major challenges for further yield improvements; in particular, imbalanced fertilization. The fertilizer recommendation and nutrient management approach, Nutrient Expert (NE) for Hybrid Maize, is a computer-based decision support system that was developed by the International Plant Nutrition Institute, which is a not-for-profit, science-based organization dedicated to the responsible management of plant nutrition for the benefit of the human family. The NE system is based on yield response and agronomic efficiency, and uses site-specific nutrient management principles and the "four R's method" (right source, right rate, right time and right place), combined with the quantitative evaluation of the fertility of tropical soils model to simulate optimal nutrient uptake (Xu et al., 2013) and to develop site-specific fertilizer recommendations (Xu et al., 2014a,b). In this paper, we applied a combined simulation and on-farm research approach to access the continual use of fertilizer recommendations from NE through: (1) quantifying yield gaps, (2) evaluating the nutrient use efficiency and economic performance, and (3) assessing the envi-

**Table 1**

Site characteristics of the field experiments.

Province	Location	No. of farm	Soil pH	OM (%) <sup>1</sup>
Heilongjiang	Qing'an	3	5.7	6.6
	Binxian	2	5.3	4.5
	Shuangcheng	4	5.8	2.6
	Minzhu	1	6.8	3.5
	Liufangzi	5	4.9	1.6
	Taojia	2	5.8	3.1
	Chaoyangpo	3	5.3	1.5

<sup>1</sup> OM: organic matter, determined by potassium dichromate oxidation-ferrous sulphate titrimetry.

ronmental performance including soil inorganic N at harvest of maize crop and GHG emissions, to prove that NE is a useful tool that should be more widely recommended.

## 2. Materials and methods

### 2.1. On-farm research approach

On-farm experiments were conducted within the major maize production zone of Northeast China, to develop and evaluate the NE decision support system. Between 2010 and 2012, a total of 145 on-farm experiments were set up in farmers' fields of Northeast China to adjust the NE system (Xu et al., 2014a). In the current study, a total of 20 on-farm location experiments were selected from the 2012 experiments and were conducted between 2012 and 2014, to validate the continual effects of NE use through examining the yield and the economic, agronomic and environmental performance of each site. The experiments were located in the Jilin (10) and Heilongjiang (10) provinces of Northeast China (Table 1).

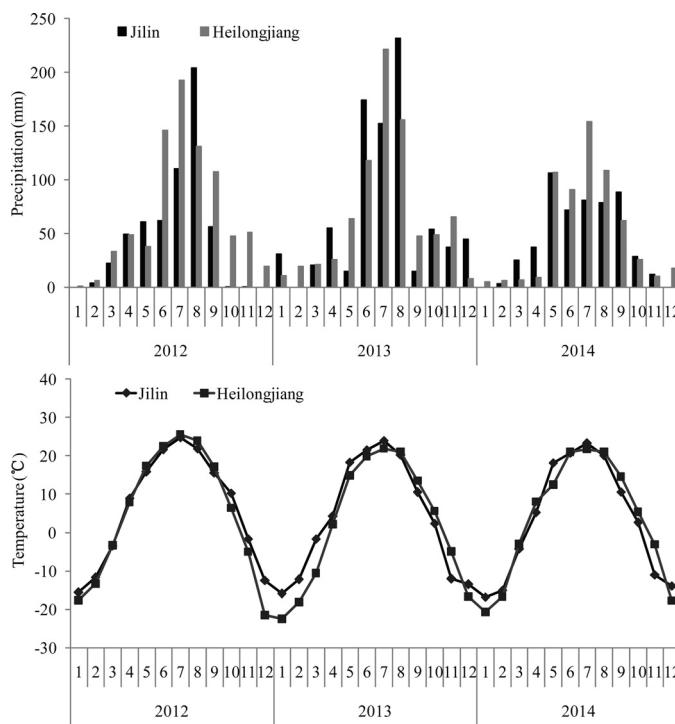
### 2.2. Treatments

All on-farm experiments followed a standardized experimental protocol. Six treatments were set for each experiment, as follows: optimum nutrient management based on NE recommendation, usual farmers' practice (FP), soil testing (OPTS) was set to validate NE's availability and efficiency, and a series of nutrient omission plots, which excluded N, P or K from the NE treatment. A large area ( $>667 \text{ m}^2$ ) was used for the NE, FP and OPTS treatments, and a smaller area ( $30 \text{ m}^2$ ) were used for the omission plots. Omission plots changed position every year on the foundation of NE treatment (a single large plot, area  $>667 \text{ m}^2$ ) and were used to estimate nutrient use efficiency of N, P and K and calculated N balance for each year. Plant density and procedures for the control of weeds, pests and diseases were identical across all plots, according to the local best management practices. Soil profile samples were collected from the top 90 cm (0–30, 30–60 and 60–90 cm) before sowing and after the maize harvest for soil nitrate-N ( $\text{NO}_3\text{-N}$ ) and ammonia-N ( $\text{NH}_4\text{-N}$ ) contents.

In the NE treatment, fertilization rates were in the following ranges: 150–208, 22–43, and 48–87 kg N, P, and K  $\text{ha}^{-1}$ , respectively. All P fertilizer was applied as basal for each treatment, N was split into two forms for application: basal fertilizer and dressed at growth stages V6–V8 with a ratio of 50:50. Fertilizer K was applied two times if the K fertilizer rate exceeded 50 kg K  $\text{ha}^{-1}$ , with a ratio of 50:50 for both basal and topdressing fertilizer (V6–V8).

In the FP treatment, fertilizer application practices were based on farmers' usual management practices with no interference by the researchers. The N, P, and K fertilizers were generally all applied as basal fertilizer. Fertilization rates were in the following ranges: 153–280, 17–72, and 32–100 kg N, P, and K  $\text{ha}^{-1}$ , respectively.

In the OPTS treatment, fertilization practices were based on soil testing. All P and K fertilizer was applied as basal for each treat-



**Fig. 1.** Monthly average precipitation (mm) and mean temperature (°C) for all locations at Jilin and Heilongjiang provinces during 2012–2014.

ment, N was split into two forms for application: basal fertilizer and dressed at growth stages V6–V8 with a ratio of 50:50. Fertilization rates for this treatment were in the following ranges: 135–240, 13–70, and 32–100 kg N, P, and K ha<sup>-1</sup>, respectively.

### 2.3. Experimental analysis

The Hybrid-Maize model was used to estimate potential yield using weather data, sowing and harvest dates, and plant population (Yang et al., 2004; Bai et al., 2010; Meng et al., 2013). The model combines the strength of different modeling approaches: the growth and development functions in maize-specific models (CERES-Maize), and the mechanistic formulation of photosynthesis and respiration in generic crop models (INTERCOM and WOFOST), and has been shown to be reasonably accurate at estimating maize potential yield (Yang et al., 2004). The climate-driven yield potential under rain-fed condition was estimated in the current study, using daily weather data (i.e., solar radiation, maximum and minimum temperatures, and precipitation) during the simulated maize seasons at each location for every year (2012–2014), and then used average value to represent all locations. Solar radiation and maximum and minimum temperatures were obtained from nearby meteorological stations (China Meteorological Data Sharing Service System, 2016). Maize varieties were chosen by the farmers and have the same approximate seeding quantity (65,000–75,000 plants ha<sup>-1</sup>) for all treatments in each experiment. The monthly precipitation and average temperature for all locations at Jilin and Heilongjiang provinces during 2012–2014 were described in Fig. 1, but the separate daily weather data was used at each location for each year to simulate potential yield.

The straw and grain sample were collected to analyze N, P and K concentration. The total nutrient uptake, nutrient use efficiency including recovery efficiency (RE), partial factor productivity (PFP), and agronomic efficiency (AE) of nutrient application were calculated as follows:

$$AE_i = (Y - Y_0)/F_i \quad (1)$$

$$RE_i = (U - U_0)/F_i \quad (2)$$

$$PFP_i = Y/F_i \quad (3)$$

where  $i$  is the nutrient (N, P, or K);  $F$  is the amount of fertilizer applied (kg ha<sup>-1</sup>);  $Y$  is the yield (kg ha<sup>-1</sup>);  $Y_0$  is the yield (kg ha<sup>-1</sup>) in the control treatment with no N, P, or K;  $U$  are the total plant nutrient uptake in above-ground biomass at maturity (kg ha<sup>-1</sup>); and  $U_0$  is total plant nutrient uptake in aboveground biomass at maturity in a plot with no N, P, or K (kg ha<sup>-1</sup>).

Economic calculations were made using U.S. dollars as standard currency:

$$TFC = P_N F_N + P_P F_P + P_K F_K \quad (4)$$

$$GRF = P_R Y_R - TFC \quad (5)$$

where TFC is total fertilizer cost (\$ ha<sup>-1</sup>);  $P_N$  is price of N fertilizer;  $F_N$  is amount of N applied (kg N ha<sup>-1</sup>);  $P_P$  is price of P fertilizer;  $F_P$  is amount of P applied (kg P ha<sup>-1</sup>);  $P_K$  is price of K fertilizer;  $F_K$  is amount of K applied (kg K ha<sup>-1</sup>); GRF is the gross return above fertilizer cost (\$ ha<sup>-1</sup>);  $P_R$  is price of maize; and  $Y_R$  is yield of maize (kg ha<sup>-1</sup>).

We also calculated the direct N<sub>2</sub>O emissions and indirect N<sub>2</sub>O emissions including ammonia (NH<sub>3</sub>) volatilization and nitrate (NO<sub>3</sub><sup>-1</sup>) leaching for spring maize. The relationship between N<sub>2</sub>O emission and N fertilizer application rate was simulated by using observed data based on empirical model to calculate direct N<sub>2</sub>O emission (Wu et al., 2014). The equation is:

$$\text{Direct N}_2\text{O emission} = 0.576 \exp(0.0049 \times \text{Nrate}) \quad (6)$$

The indirect N<sub>2</sub>O emission was estimated by the International Panel on Climate Change methodology (Klein et al., 2006), where indirect N<sub>2</sub>O emission was estimated as 1% and 0.75% of NH<sub>3</sub> volatilization and N leaching is lost as N<sub>2</sub>O, respectively. While the relationships between NH<sub>3</sub> volatilization and N fertilizer application rate, between N leaching and N fertilizer application rate were built using linear or exponential models to calculate NH<sub>3</sub> volatilization and N leaching (Cui et al., 2013).

$$\text{NH}_3 \text{ volatilization} = 0.24 \times \text{Nrate} + 1.30 \quad (7)$$

$$\text{N leaching} = 4.46 \exp(0.0094 \times \text{Nrate}) \quad (8)$$

Total greenhouse gas (GHG) emissions during the entire life cycle of maize production, including CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O (CH<sub>4</sub> emission could be ignored in agroecosystem), detailed equation is provided as below (Forster et al., 2007; Zhang et al., 2013):

$$\begin{aligned} \text{GHG} &= (\text{GHG}_m + \text{GHG}_t) \times \text{Nrate} + \text{total N}_2\text{O} \times 44/28 \times 298 \\ &\quad + \text{GHG others} \end{aligned} \quad (9)$$

where GHG represents the total GHG emission calculated as CO<sub>2</sub> eq, GHG<sub>m</sub> is the GHG emission factor of N product manufacturing and GHG<sub>t</sub> is the GHG emission factor of N fertilizer transportation, GHG<sub>others</sub> represents GHG emission of P and K fertilizer production and transportation (GHG<sub>m</sub> and GHG<sub>t</sub> were 8.21 and 0.09 kg CO<sub>2</sub> eq ha<sup>-1</sup>; GHG<sub>others</sub> for P and K were 0.79 and 0.55 kg CO<sub>2</sub> eq ha<sup>-1</sup>). GHG emission intensity was expressed as kg CO<sub>2</sub> eq t<sup>-1</sup> grain.

The ANOVA analysis from SPSS 13.0 software were performed on the differences among NE, FP and OPTS at 0.05 level.

## 3. Results

### 3.1. Potential yield and yield gap

The results indicated that the potential yield in 2012 (16.9 t ha<sup>-1</sup>) was higher than in 2013 (14.0 t ha<sup>-1</sup>) and 2014 (15.1 t ha<sup>-1</sup>) (Table 2). On average, the simulated potential yield

**Table 2**

Modeled potential yields using the Hybrid-Maize model, and grain yields for Nutrient Expert (NE), farmers' practices (FP) and soil testing (OPTS) and their yield gaps.

Year	Treatment	Grain yield ( $\text{t ha}^{-1}$ )	Potential yield ( $\text{t ha}^{-1}$ ) <sup>1</sup>	Percent (%) <sup>2</sup>	Yield gap <sup>3</sup>	$P > [T]$ <sup>4</sup>
2012	NE	12.7	16.9	75	–	–
	FP	11.7		69	1.0	<0.001
	OPTS	12.0		71	0.7	0.016
2013	NE	12.4	14.0	88	–	–
	FP	11.6		83	0.8	<0.001
	OPTS	12.4		88	0.0	0.143
2014	NE	11.6	15.1	77	–	–
	FP	10.8		71	0.8	<0.001
	OPTS	11.1		74	0.5	0.001
All	NE	12.3	15.4	80	–	–
	FP	11.4		74	0.9	<0.001
	OPTS	11.8		77	0.5	<0.001

<sup>1</sup> The potential yield is an average yield for all sites in 2012, 2013, 2014 and across all years, respectively.

<sup>2</sup> The number are the yield as a percentage of potential yield for different treatments.

<sup>3</sup> FP and OPTS correspond to the yield gap between NE and FP, and between NE and OPTS, respectively.

<sup>4</sup> FP and OPTS correspond to  $P$ -value are the probability of a significant mean difference in yield gap between NE and FP, and between NE and OPTS, respectively.

based on the Hybrid-Maize model over the three studied years was  $15.4 \text{ t ha}^{-1}$ , with a minimum of  $12.8 \text{ t ha}^{-1}$  (at Binxian in 2013) and a maximum of  $17.9 \text{ t ha}^{-1}$  (at Qing'an in 2012). The potential yield is largely dependent on weather conditions and shows a substantial 10% variation. In the NE treatment, the three-year average yield was  $12.3 \text{ t ha}^{-1}$  across all sites, with a range of  $11.6\text{--}12.7 \text{ t ha}^{-1}$ , and accounted for 80% of the potential yield. However, the yield in the OPTS and FP treatments were  $11.8$  and  $11.4 \text{ t ha}^{-1}$ , and account for 77% and 74% of the potential yield, respectively. On average, the yield gap between NE and FP was  $0.9 \text{ t ha}^{-1}$  ( $P < 0.001$ ), and there were similar yield gaps for every year, with values of 1.0, 0.8, and  $0.8 \text{ t ha}^{-1}$  in 2012, 2013, and 2014, respectively. The yield gap between the OPTS and FP treatments was  $0.4 \text{ t ha}^{-1}$ , but the yield of the OPTS treatment was  $0.5 \text{ t ha}^{-1}$  lower than that of the NE treatment ( $P < 0.001$ ). Compared with the OPTS treatment, the NE treatment showed a stable yield improvement effect in the spring maize production of Northeast China.

### 3.2. Fertilizer application and economic efficiency

Further increases in maize yield with good economic returns are feasible in Northeast China through relatively straightforward adjustments in crop and nutrient management (Table 3). In the current study, average fertilizer N input was  $207 \text{ kg N ha}^{-1}$  in the FP treatment, in which 70% of all sites had a fertilizer application rate higher than  $180 \text{ kg N ha}^{-1}$ . The maximum N fertilizer input in the FP treatment ( $280 \text{ kg N ha}^{-1}$  in Taojia of Jilin province) was about  $110 \text{ kg N ha}^{-1}$  greater than the N uptake in the above-ground matter ( $170 \text{ kg N ha}^{-1}$ ). On average, there was a similar N fertilizer input between the NE ( $173 \text{ kg N ha}^{-1}$ ) and OPTS ( $179 \text{ kg N ha}^{-1}$ ), which were 34 and  $28 \text{ kg N ha}^{-1}$  lower than the FP treatment across all sites (significant at  $P < 0.001$ ), representing a 16% and 14% decrease, respectively. The fertilizer N in the NE treatment increased from 2012 ( $165 \text{ kg N ha}^{-1}$ ) to 2014 ( $179 \text{ kg N ha}^{-1}$ ) because the NE approach is a dynamic nutrient management method that adjusts the amount of fertilizer according to residual N, yield response to N application, and the indigenous N supply from the previous crop. In the current study, the relative yield (the ratio of yield between the N omission treatment and the NE treatment) decreased from 2012 (0.76) to 2014 (0.68) (data not shown), which resulted in an increased amount of N fertilizer use.

On average, P fertilizer input in the NE treatment was higher ( $4 \text{ kg P ha}^{-1}$ ) than in the OPTS treatment, but both treatments had the similar K fertilizer input. However, the NE and OPTS treatments saved a significant amount of fertilizer P ( $8$  and  $12 \text{ kg P ha}^{-1}$ ,  $P < 0.001$ ) compared with the FP treatment, representing a decrease of 20% and 30%, respectively (Table 3). The maximum P fertilizer

input ( $72 \text{ kg P ha}^{-1}$ ) for the FP treatment was about double the P uptake in the above-ground matter ( $33 \text{ kg P ha}^{-1}$ ), which would lead to considerable P accumulation in the soil. However, K input is the opposite; compared with the FP treatment, average K fertilizer application in the NE and OPTS treatments were more than 8 and  $9 \text{ kg K ha}^{-1}$  greater than in the FP treatment ( $P = 0.002$ ), representing an increase of 13% and 15%, respectively.

There was a slightly lower TFC ( $\text{US\$4 ha}^{-1}$ ) in the NE treatment than in the OPTS treatment, but TFC in the NE treatment was significantly lower ( $\text{US\$26 ha}^{-1}$ ,  $P = 0.01$ ) than in the FP treatment across all sites (Table 3). Use of NE saved  $\text{US\$26 ha}^{-1}$  and  $\text{US\$14 ha}^{-1}$  of N and P fertilizer cost, relative to the FP treatment, respectively. However, an additional  $\text{US\$14 ha}^{-1}$  was paid for K fertilizer input. The GRF in the NE treatment ( $\text{US\$3727 ha}^{-1}$ ) was significantly higher than in the FP treatment ( $\text{US\$3424 ha}^{-1}$ ) ( $P < 0.001$ ), and the OPTS treatment ( $\text{US\$3560 ha}^{-1}$ ) ( $P = 0.001$ ), increased by  $\text{US\$303}$  and  $\text{US\$167}$  across all sites, respectively, in which about 91% and 98% of increase GRF was attributed increase in grain yield rather than reduction in fertilizer cost, respectively.

### 3.3. Nutrient use efficiency

The NE treatment had considerably higher N use efficiency than the FP treatment for each year (Table 4). On average, REN, AEN and PFPP under the NE treatment were significantly higher than in the FP treatment ( $P < 0.001$ ), showing increases of 12%,  $6 \text{ kg kg}^{-1}$ , and  $14 \text{ kg kg}^{-1}$ . In the NE treatment, REN, AEN and PFPP also higher than found in the OPTS treatment, increased by 4%,  $1 \text{ kg kg}^{-1}$  and  $4 \text{ kg kg}^{-1}$ , respectively. The AEN and PFPP in the NE treatment were  $6 \text{ kg kg}^{-1}$  and  $11 \text{ kg kg}^{-1}$  greater than those obtained by Gao et al. (2012), respectively.

The P use efficiency was significantly higher under the NE treatment than under the FP treatment for each year, with the exception of PFPP in 2013 (Table 4). On average, REP, AEP and PFPP under the NE treatment were 31%,  $60 \text{ kg kg}^{-1}$  and  $402 \text{ kg kg}^{-1}$ , compared with 16%,  $25 \text{ kg kg}^{-1}$  and  $357 \text{ kg kg}^{-1}$  under the FP treatment, representing increases of 15%,  $35 \text{ kg kg}^{-1}$  and  $45 \text{ kg kg}^{-1}$ , respectively. In Heilongjiang province, the P fertilizer application rate averaged  $25 \text{ kg P ha}^{-1}$  under the FP treatment, compared with  $32 \text{ kg P ha}^{-1}$  under the NE treatment, and the minimum value was only  $17 \text{ kg P ha}^{-1}$ , which led to a higher PFPP under the FP treatment ( $501 \text{ kg kg}^{-1}$ ) than under the NE treatment ( $402 \text{ kg kg}^{-1}$ ). Nonetheless, the high REP and AEP values were obtained under the NE treatment, rather than under the FP treatment. However, the PFPP under the NE treatment ( $401 \text{ kg kg}^{-1}$ ) in Jilin province was above  $189 \text{ kg kg}^{-1}$  than in FP treatment ( $212 \text{ kg kg}^{-1}$ ) due to NE saved  $24 \text{ kg P ha}^{-1}$  compared with FP. The REP and AEP values were higher

**Table 3**

Fertilizer input, total fertilizer cost (TFC) and gross return above fertilizer cost (GRF) for Nutrient Expert (NE), farmers' practices (FP) and soil testing (OPTS).

Year	Treatment	Fertilizer rate ( $\text{kg ha}^{-1}$ )			TFC ( $\text{US\$ ha}^{-1}$ )	GRF ( $\text{US\$ ha}^{-1}$ )	$\Delta^2$	$P > [T]^3$
		N	P	K				
2012	NE	165 b <sup>1</sup>	26 b	65 ab	269 b	3876 a	–	–
	FP	207 a	40 a	61 b	318 a	3517 b	359	<0.001
	OPTS	167 b	27 b	73 a	287 ab	3612 b	263	0.016
2013	NE	175 b	36 ab	73 a	301 a	3724 a	–	–
	FP	207 a	40 a	61 b	314 a	3458 b	266	<0.001
	OPTS	186 b	28 b	68 ab	298 a	3693 a	31	0.209
2014	NE	179 b	34 ab	71 a	303 a	3581 a	–	–
	FP	207 a	40 a	61 a	318 a	3298 a	284	<0.001
	OPTS	186 b	28 b	68 a	299 a	3376 a	206	0.001
All	NE	173 b	32 b	69 a	291 b	3727 a	–	–
	FP	207 a	40 a	61 b	317 a	3424 b	303	<0.001
	OPTS	179 b	28 b	70 a	295 ab	3560 b	167	0.001

<sup>1</sup> The comparisons are within columns among NE, FP and OPTS in 2012, 2013, 2014 and across all years, respectively. The data for N, P and K fertilizer are on an elemental basis. Values followed by different letters for different treatments are significantly different at the 0.05 probability level.

<sup>2</sup>  $\Delta$ : FP and OPTS correspond to the GRF gap between NE and FP, and between NE and OPTS, respectively.

<sup>3</sup> FP and OPTS correspond to  $P$ -value are the probability of a significant mean difference between NE and FP, and between NE and OPTS for GRF, respectively.

**Table 4**

Recovery efficiency (RE), agronomic efficiency (AE) and partial factor productivity (PFP) to N, P and K fertilizer application for Nutrient Expert (NE), farmers' practices (FP) and soil testing (OPTS).

Year	Treatment	RE (%)			AE ( $\text{kg kg}^{-1}$ )			PFP ( $\text{kg kg}^{-1}$ )		
		N	P	K	N	P	K	N	P	K
2012	NE	33 a	47 a	55 a	18 a	88 a	30 a	77 a	501 a	201 ab
	FP	21 b	25 b	41 b	11 b	34 b	17 b	59 b	371 b	217 a
	OPTS	30 a	38 a	39 b	17 a	64 a	17 b	73 a	476 a	171 b
2013	NE	33 a	17 ab	46 a	19 a	41 a	20 a	71 a	350 a	175 b
	FP	22 b	11 b	42 a	13 b	19 b	12 b	59 b	372 a	218 a
	OPTS	30 a	28 a	44 a	19 a	47 a	19 a	67 a	440 a	189 b
2014	NE	39 a	28 a	36 a	21 a	51 a	22 a	66 a	354 a	167 b
	FP	27 c	11 b	24 b	14 c	22 b	12 b	53 b	328 a	195 a
	OPTS	32 b	25 a	28 b	17 b	48 a	19 ab	61 a	401 a	169 b
All	NE	35 a	31 a	46 a	19 a	60 a	24 a	71 a	402 ab	181 b
	FP	23 c	16 b	36 b	13 b	25 b	14 c	57 b	357 b	210 a
	OPTS	31 b	31 a	37 b	18 a	53 a	18 b	67 a	439 a	176 b

The comparisons are within columns among NE, FP and OPTS in 2012, 2013, 2014 and across all years, respectively. The data for nutrient N, P and K efficiencies are on an elemental basis. Values followed by different letters for different treatments are significantly different at the 0.05 probability level.

under the NE treatment than under the OPTS treatment; however, PFP was 37  $\text{kg kg}^{-1}$  lower because the P fertilizer application rate was above 4  $\text{kg P ha}^{-1}$  in the NE treatment than in the OPTS treatment, while the yield gap between the NE and OPTS treatments was only 0.5  $\text{t ha}^{-1}$ .

The REK and AEK values were significantly higher under the NE treatment than under the FP treatment, even though the K fertilizer input in the NE treatment was 8  $\text{kg K ha}^{-1}$  higher than in the FP treatment. On average, REK and AEK under the NE treatment were 46% and 24  $\text{kg kg}^{-1}$ , compared with 36% and 14  $\text{kg kg}^{-1}$  under the FP treatment, representing increases of 10% and 10  $\text{kg kg}^{-1}$ , respectively. However, the PFPK under the NE treatment (181  $\text{kg kg}^{-1}$ ) was lower than that under the FP treatment (210  $\text{kg kg}^{-1}$ ), representing a decrease of 29  $\text{kg kg}^{-1}$ . This was because the K fertilizer application under the FP treatment was lower than that under the NE treatment. There was the similar K fertilizer input in both NE and OPTS treatments; however, the differences of REK, AEK and PFPK values were 9%, 6  $\text{kg kg}^{-1}$  and 5  $\text{kg kg}^{-1}$  between NE and OPTS, indicating that balanced fertilization plays an important role in increasing K use efficiency.

#### 3.4. Apparent N loss and GHG emissions

The three years of results indicated that use of NE produced a high yield with low environmental pollution, compared with the FP

treatment (Table 5). Based on the three-year total calculated N balance, N fertilizer application under the NE treatment (519  $\text{kg ha}^{-1}$ ) was lower than under the FP treatment (622  $\text{kg ha}^{-1}$ ), but N uptake in the above-ground under the NE treatment (569  $\text{kg ha}^{-1}$ ) was 39  $\text{kg N ha}^{-1}$  greater than that under the FP treatment (530  $\text{kg ha}^{-1}$ ). This suggests that a more balanced NPK nutrition can promote N uptake without relying on high N fertilizer input. The high N fertilizer input also led to soil inorganic N accumulation at harvest of maize crop; the results indicated that the residual N at harvest in 2014 under the NE treatment (86  $\text{kg ha}^{-1}$ ) was significantly lower ( $P < 0.001$ ) than that under the FP treatment (149  $\text{kg ha}^{-1}$ ), representing a decrease of 63  $\text{kg ha}^{-1}$ .

The three-year total GHG emissions under the NE treatment would decrease by 17%, from 8849 to 7359  $\text{kg CO}_2 \text{ eq ha}^{-1}$ , compared with the FP treatment (Table 5), and total  $\text{N}_2\text{O}$  emission would decrease by 14%, from 7 to 6  $\text{kg ha}^{-1}$ . The overuse of N fertilizer under the FP treatment resulted in a high GHG emission intensity, compared with the NE (an increase of 23%, from 203 to 262  $\text{kg CO}_2 \text{ eq t}^{-1}$  grain). Relative to the OPTS treatment, the NE treatment not only saved N fertilizer (19  $\text{kg N ha}^{-1}$ ) and increased N uptake (15  $\text{kg N ha}^{-1}$ ), but also reduced residual N at harvest (27  $\text{kg ha}^{-1}$ ). Furthermore, total GHG emissions and GHG emission intensity decreased by 240  $\text{kg CO}_2 \text{ eq ha}^{-1}$ , and 15  $\text{kg CO}_2 \text{ eq t}^{-1}$  grain, respectively.

**Table 5**

Nitrogen balances and greenhouse gas (GHG) emissions for nutrient expert (NE), farmers' fertilizer practice (FP) and soil testing (OPTS) treatments for a three-year interval from the start of the 2012 season to the end of the 2014 season.

Parameter	NE	FP	OPTS	ΔNE-FP	ΔNE-OPTS
$N_{\text{initial}} (\text{kg ha}^{-1})$	177	177	177	–	–
Total $N_{\text{fertilizer}} (\text{kg ha}^{-1})$	519	622	538	–103	–19
Total $N_{\text{uptake}} (\text{kg ha}^{-1})$	569	530	554	39	15
$N_{\text{residual}} (\text{kg ha}^{-1})$	86	149	113	–63	–27
Total $N_2O$ emission ( $\text{kg ha}^{-1}$ )	6	7	6	–1	0
Total GHG emissions ( $\text{kg CO}_2 \text{ eq ha}^{-1}$ )	7359	8849	7599	–1490	–240
GHG emission intensity ( $\text{kg CO}_2 \text{ eq t}^{-1} \text{ grain}$ )	203	262	218	–59	–15

$N_{\text{initial}}$ : residual  $\text{NO}_3-\text{N}$  and  $\text{NH}_4-\text{N}$  in 0–90 cm soil depth before sowing in 2012;  $N_{\text{fertilizer}}$ : N fertilizer rate;  $N_{\text{uptake}}$ : N uptake by above-ground parts at harvest;  $N_{\text{residual}}$ : residual  $\text{NO}_3-\text{N}$  and  $\text{NH}_4-\text{N}$  in 0–90 cm soil depth after harvest in 2014.

#### 4. Discussion

There is no doubt that the use of improved varieties, soil fertility management, water and weed management account for a large proportion of the yield gains obtained in China over the past decade. However, quantifying the gaps between the potential yield, experimental yield and the farmers' yield is essential for furthering research and formulating policies for food security and environmental protection at regional, national, and even international levels (Van Ittersum et al., 2013; Van Wart et al., 2013). There were considerable yield-improvement opportunities exist relative to current attainable yield ceilings, if closing yield gap to 100% of attainable yield could increase worldwide maize production by 64% (Mueller et al., 2012). Pasuquin et al. (2014) showed that the average exploitable yield gap between the attainable yield and current farmers' yield in Southeast Asia can reach  $0.9 \text{ t ha}^{-1}$  through site-specific nutrient management. The potential yield in our study was identical to that reported by Meng et al. (2013), and higher than reported by Lv et al. (2015) ( $15.1 \text{ t ha}^{-1}$ ). However, the three treatment yields (NE, FP, and OPTS) in the current study have increased considerably above those of past decades, which is mainly because of improved cultivars, fertilization and agricultural practices. There was a large production increase (8%) in our study from the changes of nutrient management practices, which were tailored to field-specific conditions for crop yield, crop residue management, historical fertilizer use, and use of organic materials. The yield obtained from NE in our study was greater than the value of  $2.5 \text{ t ha}^{-1}$  than that of Gao et al. (2012), who based their study on 737 on-farm experiments using the recommended N rate in Jilin province of China. However, the yields in the three treatments in the current study were all lower than the highest recorded yield ( $15.8 \text{ t ha}^{-1}$ ) in Northeast China reported by Meng et al. (2013).

Mineral fertilizers play a decisive role in narrowing the yield gap. However, excessive or imbalanced fertilizer use not only results in a large yield gap, but also contributes to low nutrient use efficiency. Large reductions in total fertilizer N use under the NE treatment contributed to the overall higher N use efficiency compared with the FP treatment. The low N use efficiency was strongly related to the high soil indigenous N supply (average of  $127 \text{ kg N ha}^{-1}$  from N omission treatment in the current study), which mainly originates from residual N from the previous crop (more than  $200 \text{ kg N ha}^{-1}$  in the FP treatment) and atmospheric deposition (about  $21 \text{ kg N ha}^{-1}$ ) (Liu et al., 2013), in addition, net N mineralization of organic N from organic matter is an important source of N availability to corn, because more than  $30 \text{ kg N ha}^{-1}$  per year would be mineralized for every 1% soil organic matter (Soltanpour, 1979; Schepers and Mosier, 1991). The progress has been made with NE in improving fertilizer use for maize, while the findings of this study indicate that N fertilizer maybe is over applied with NE, and scope for further improvement in N use efficiency remains with NE, because the REN (35%) and AEN ( $19 \text{ kg kg}^{-1}$ ) measured in the NE treatment in current study were also lower than the target values of 50% and  $25 \text{ kg kg}^{-1}$  for well-managed maize systems proposed by Dobrmann (2007).

The effective management of P and K has been described for maize in many reports (Wortmann et al., 2009; Xu et al., 2014b). Soil testing and crop-based approaches have been developed and widely used in P and K management guidance for farmers (He et al., 2009; Pampolini et al., 2012; Xu et al., 2014a). Most agricultural crops recovered 20–30% of applied P during their growth under favorable growth conditions, and realistic targets of 40–60% have been set for REK under soil with low available K reserves (Dobermann, 2007). Relatively high RE values for P (31%) and K (46%) were obtained in our study, because NE gives a dynamic/different fertilizer recommendation because of the different environmental conditions in different years and also because of the potentially different management of previous residual nutrients (fertilizer rate applied, retained straw from previous crops). Moreover, the NE method takes advantage of the soil indigenous nutrient supply and residual nutrients from previous crops in an attempt to avoid excessive nutrient accumulation in the soil and has been applied with success in some countries (Witt et al., 2007; Buresh et al., 2010; Pampolini et al., 2011). In addition, a more balanced NPK nutrition in the NE treatment might have also led to increases in nutrient use efficiency through more vigorous plant growth and greater resistance to diseases.

Numerous research results have shown that excessive N fertilization results in serious environmental problems in intensively cultivated areas through emission, leaching and runoff (Ju et al., 2009; Zhang et al., 2013). Direct GHG emissions from global agriculture represented 14% of total global anthropogenic emissions of GHG (IPCC, 2014). There is an exponential relationship between  $N_2O$  emissions and N fertilizer input (Mcswiney and Robertson, 2005; Hoben et al., 2011; Cui et al., 2013). The GHG emission from N fertilizer used for crop application occupies a major proportion of the total agricultural emissions in China (Liu and Zhang, 2011). Therefore, effective integrated management is required to increase yield without increasing environmental pollution. Ju et al. (2009) reported that a better N balance can be achieved without sacrificing crop yields with 30%–60% N savings in China by adopting optimum N fertilization techniques, controlling the primary N loss pathways, and improving the performance of the agricultural extension service. Cui et al. (2013) showed that the  $N_2O$  emission intensity and the GHG intensity can be reduced by 12% and 19%, respectively, for maize by using an integrated soil-crop system approach. However, the N addition from sources other than N fertilizer (such as residual N and environmental N included irrigation and atmospheric deposition) must also be considered in the development and application of optimal practices for fertilization.

#### 5. Conclusions

The nutrient management strategies in intensive maize systems in China must become more site-specific and dynamic, to manage spatially and temporally variable resources based on a quantitative understanding of the congruence between nutrient

supply and crop demand, because modern agriculture needs to find environmentally friendly ways to increase production and prompt sustainable development of agriculture. Nutrient Expert for Hybrid Maize strategies include site- and season-specific knowledge of crop nutrient requirements and soil indigenous nutrient supplies are required to increase crop yield and nutrient use efficiency with low apparent N loss and low GHG emissions. In the current study, grain yield increases averaging  $0.9\text{ t ha}^{-1}$ , increased AEN and REN by approximately 50%, and doubled AEP and REP based on the use of the Nutrient Expert for Hybrid Maize tool compared with current farming practices. Importantly, there was a decrease in GHG emission intensity of 23%. The integration of appropriate nutrient management strategies with related agronomic practices is the key to more productive, profitable and environmentally sustainable crop management practices. We conclude that the Nutrient Expert for Hybrid Maize system has the potential to close existing yield gaps in the spring maize production systems of Northeast China by improving yield, nutrient use efficiency, and profitability with low environmental pollution.

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