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Estimating a new approach of fertilizer recommendation across small-holder farms in China

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ABSTRACT

Over and imbalanced fertilization has caused a series of environmental problems and threaten the food security in China. On-farm experiments were conducted from 2010 to 2012 at 408 sites in seven provinces to evaluate a new fertilizer recommendation approach, Nutrient Expert (NE) for Hybrid Maize (*Zea mays* L.), to meet the requirements of nutrient management for small-holder farms in China. Compared with the current farmers' fertilizer practices (FP), NE maintained grain yield and profitability, but decreased 30.4% of nitrogen (N) fertilizer (68 kg N ha^{-1}) and 11.3% of phosphorus (P) fertilizer (7 kg P_2O_5 ha^{-1}), while potassium (K) fertilizer rate increased by 38.8% (19 kg K_2O ha^{-1}). NE increased agronomic efficiency of applied N (AE_N) by 47.0%, N recovery efficiency (RE_N) by 51.0%, and partial factor productivity of applied N (PFP_N) by 35.5%. More importantly, NE decreased by 21.5 and 49.7 kg ha^{-1} of apparent N loss for summer maize and spring maize as compared with FP, respectively. The differences in agronomic and environmental parameters between NE and FP confirmed that the Nutrient Expert for Hybrid Maize is a promising nutrient decision support tool which not only increasing grain yield, nutrient use efficiency and profit, but also reducing nutrient loss and environmental pollution.

1. Introduction

Increases in food requirements, along with the decreasing arable land resources will generate great pressure on grain production in the future. A lot of research has shown that over-fertilization by farmers driven by the desire for higher yields does not always contribute to increase yield, however, this over-fertilization causes fertilizer waste and negative effects on the environment (Ju et al., 2009). Water pollution (Le et al., 2010), greenhouse gases emission (Zheng et al., 2004), nutrient accumulation in soil (Chen et al., 2006) and nutrient leaching (Zhang et al., 2005) due to over fertilization have become more and more serious problems in China. Typical N rate for some farmers have exceeded 500 kg ha^{-1} $year^{-1}$ for intensive wheat–maize systems in China (Cui et al., 2010a). Therefore, it is urgent to find a suitable fertilizer recommendation method, which can not only meet crop nutrient requirements for high yield, but also benefit the environment.

Numerous researches have been done to improve the use of indigenous soil nutrients, fertilizer use efficiency, and increase yield to its maximum potential. These included optimal N rate based on testing soil NO_3-N content in root layer (Cui et al., 2010b), fertilizer recommendation based on soil testing and yield targets and crop responses (He et al., 2009), fertilizer effect function equation (Sonar and Babhulkar, 2002), etc. These methods were effective for fertilizer recommendation, but they generally need comprehensive field sampling or annual setting field experiments due to the differences among soil types and climates in China. In addition, the past fertilizer recommendation usually involved in single nutrient, and the interaction among N, P and K were not considered.

Abbreviations: AE_N, Agronomic efficiency of applied N; FP, Farmers' fertilizer practice; GRF, Gross return above fertilizer cost; IKS, Indigenous potassium supply; INS, Indigenous nitrogen supply; IPS, Indigenous phosphorus supply; NE, Nutrient Expert; PFP_N, Partial factor productivity of applied N; RE_N, Recovery efficiency of applied N; TFC, Total fertilizer cost.

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Here, we used large number of field-based academic research results to develop a dynamic field-specific management method, nutrient expert (NE) for hybrid maize, to optimize the supply and crop demand for nutrients and achieve balanced plant nutrition, and offered the advantage that agronomists, extension workers, and farmers could work together on the farm to estimate fertilizer nutrient requirements (Witt and Dobermann, 2002). The method is associated with the site-specific nutrient management (SSNM) principles, quantitative evaluation of the fertility of tropical soils (QUEFTS) model and meanwhile considers environmental, economic and agronomic benefits to determine the requirements of N, P, and K fertilizers. The SSNM strategies could increase yields through improving nutrients and crop managements. The core of SSNM method centers on determining fertilizer rate based on soil indigenous nutrient supply, crop yield and crop nutrient uptake (Dobermann and White, 1998; Dobermann and Witt, 2004; Koch et al., 2004; Witt et al., 2006; Dobermann et al., 2002; Buresh, 2009), and finally reduces a series of environmental problems including eutrophication of surface waters, nitrate pollution of groundwater, greenhouse gas emissions, and other forms of air pollution because of large inputs of synthetic N and P fertilizer (Ju et al., 2009). The QUEFTS model was used to develop relationships between grain yield and nutrient uptake in total above-ground dry matter at different levels of target yield (Janssen et al., 1990; Smaling and Janssen, 1993; Witt et al., 1999; Chuan et al., 2013a; Xu et al., 2013). A large dataset (n = 5000) from field experiments were collected from 2001 to 2010 to estimate balanced nutrient requirements used QUEFTS model (Xu et al., 2013). Understanding nutrient uptake at target yield contributes to optimize fertilizer rate, calculate nutrient balance and helps to lessen pollution from fertilizer application (Chuan et al., 2013b; Xu et al., 2014).

The aim of this study is to evaluate the method, nutrient expert (NE) for hybrid maize, to meet the requirements of nutrient management for small-holder farms in China through field experiments conducted across seven provinces from 2010 to 2012 in Northeast and North Central China. Grain yield, nutrient uptake and efficiency parameters were collected to evaluate the agronomic performance, and fertilizer cost and net profit over fertilizer cost were assessed to evaluate the economic performance. Finally, the apparent nitrogen losses were analyzed between NE and farmers' practice (FP) to evaluate the environmental performance of the Nutrient Expert for Hybrid Maize decision support system.

2. Materials and methods

2.1. Software configuration

The nutrient expert (NE) for hybrid maize uses SSNM principles, which based on yield response (YR) and agronomic efficiency (AE), and the QUEFTS simulated optimal nutrient uptake. As a computer-based decision support tool, it contains five modules: (1) current NM practice, (2) planting density, (3) SSNM rates, (4) sources and

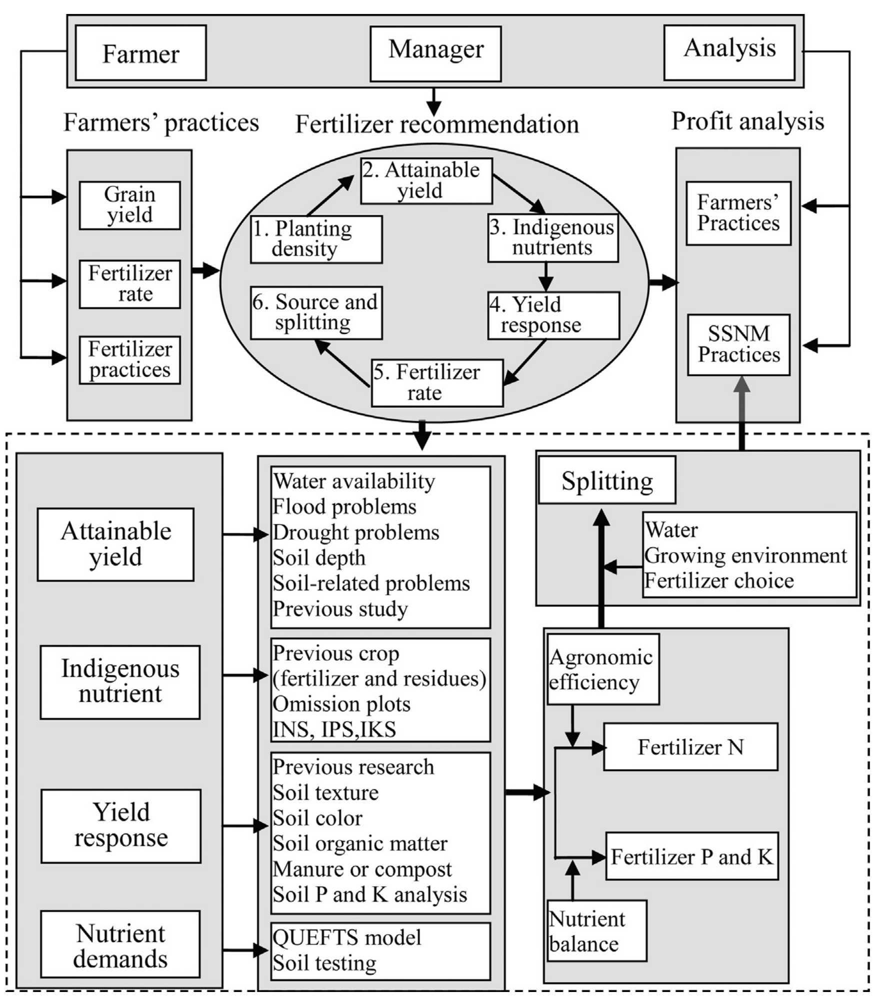

Fig. 1. The components and decision flow chart of Nutrient Expert for Hybrid Maize.

splitting, and (5) profit analysis. NE approach includes questions that determine attainable yield and yield responses to fertilizer, and provides the opportunity to integrate the 4Rs principles (right source, right rate, right time, and right place) into a fertilizer recommendation. NE method can work with or without soil testing, and can provide field specific nutrient recommendation to millions of small-holder farmers who do not have access to soil testing, especially for multiple cropping systems. More importantly, NE takes into account environmental, economic and agronomic benefits simultaneously.

NE software requires information that can be easily provided by the farmer or local crop expert, and will give guidelines on fertilizer management that are tailored to the specific field and locally-available fertilizer sources. Several questions related to environments like water availability, flooding and drought problems, and soil-related problems such as acidity and saline soils are embedded into NE software to estimate attainable yield and yield response. Fertilizer recommendation is also given based on in-season weather condition. The determination of fertilizer N requirements was mainly based on expected yield response to fertilizer and target agronomic efficiencies of applied N (AE_N). The determination of fertilizer P and K requirements considers the internal efficiency combined with estimates of attainable yield, nutrient balance and yield responses to the added nutrient within specific field (Chuan et al., 2013b; Pampolino et al., 2012). The P and K balances were estimated and used to predict the residual P and K resulting from the previous crop. N fertilizer was recommended as split application to meet the crop's N requirements during the critical growth stages. NE method can adjust fertilizer rate depending on site information which is related to weather or environmental conditions. NE gives a dynamic/different fertilizer recommendation due to the different environmental condition across different years and also the possible different management from previous residual nutrient (fertilizer rate applied, retained straw from previous crops) and not fixed across various years. Meanwhile, NE method makes advantage of soil indigenous nutrient supply and residual nutrient 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; Pampolino et al., 2011). It is a newly developed fertilizer recommendation method for maize in China (Fig. 1).

2.2. On-farm experiments

The experiments were located in China's main maize-production regions in Northeast (including Jilin (JL), Liaoning (LN), Heilongjiang (HLJ)) and North Central China (including Shanxi (SX), Shandong (SD), Henan (HN) and Hebei (HB)), which represent 29% and 32% of national maize planting area, respectively (China agriculture statistical report, 2010). Northeast is dominated by cool temperate climate with fully rainfed and single cropping of spring maize grown from April to mid- or late September using hybrid maize variety. North Central China is dominated by a temperature climate with irrigated winter wheat-summer maize rotation grown from mid-June to late September or early October (Table 1).

On-farm experiments were conducted from 2010 to 2012 in 408 farmers' fields to test the performance of NE approach on maize in agronomic, economic and environmental aspects. Maize varieties were chosen by the farmers and have the same seeding quantity for all treatments ranging from 65,000 to 75,000 plants per hectare. The selected varieties by farmers usually are currently popular varieties in China (Zhengdan958, Xianyu335, Xundan20, Xundan18, Zhongke11, Liyu16, Ludan981, BaoyuL2, Jidan27, Haiyu15). Water management and control of weeds, pests and diseases were conducted by farmers based on management practices for high yields. Farmers' practices on fertilizer application and crop management for the previous season were collected to run NE software to produce optimized nutrient management practices for the current season crop.

Five treatments were set for every field experiment included a nutrient expert (NE): the treatment was located within the farmer's field and fertilizer application was based on NE software with fertilization rates ranging from 110 to 231, 31 to 89, and 28 to 108 kg N, P_2O_5, and K_2O ha^{-1}, respectively (area ≥ 667 m^2); farmers' fertilizer practices (FP): a single large plot (area ≥ 667 m^2) and fertilizer application was done by the farmers with no interference by the researcher. Fertilizer rates in FP across different farmer's fields ranged from 48 to 460, 0 to 252, and 0 to 177 kg N, P_2O_5, and K_2O ha^{-1}, respectively; and a series of nutrient omission plots, which excluded N, P or K from the OPT-NE treatment. Fertilizer sources used were urea granules, triple super phosphate, diammonium hydrogen phosphate, potassium chloride, and potassium sulfate. Omission plots were used to estimate

Table 1
Site characteristics of the field experiments in seven provinces of China.

Province[a]	Maize season[b]	Year	No. of farms	No. of Village	Main soil types	pH	OM[c] (%)	Precipitation (mm)	Latitude (°N)	Longitude (°E)
JL	Spring	2010	9	2	Black soil	4.65–7.78	1.18–3.25	400–900	40.89–46.28	121.65–131.29
		2011	28	5						
		2012	24	4						
LN	Spring	2011	21	4	Black soil,	4.73–8.34	0.10–1.43	450–900	39.05–43.52	118.86–125.76
		2012	20	2	cinnamon soil					
HLJ	Spring	2011	26	8	Black soil	5.12–8.88	0.44–6.67	400–650	43.45–53.53	121.22–135.07
		2012	17	6						
SX	Summer	2010	7	1	Cinamon soil,	7.36–9.27	0.39–1.14	450–700	31.70–34.57	105.48–111.02
		2011	25	2	fluvo-aquic soil					
		2012	7	3						
SD	Summer	2010	17	1	Flavo-aquic soil,	8.09–9.01	0.25–0.72	550–900	34.42–38.38	114.60–112.72
		2011	11	2	cinamon soil,					
		2012	21	4	brown soil					
HN	Summer	2010	59	15	Flavo-aquic soil,	4.54–8.46	0.24–1.33	500–900	31.41–36.37	110.39–116.62
		2011	32	3	cinamon soil,					
		2012	21	3	brown soil					
HB	Summer	2010	27	1	Flavo-aquic soil,	7.47–8.36	0.41–0.92	450–700	36.08–42.67	113.45–119.83
		2011	17	2	cinamon soil					
		2012	19	2						

[a] Province: Jilin (JL), Liaoning (LN), and Heilongjiang (HLJ), Shanxi (SX), Shandong (SD), Henan (HN), Hebei (HB) provinces in China.
[b] Spring: spring maize; summer: summer maize.
[c] OM: organic matter.

indigenous nutrients supply, and also used for the determination of N use efficiencies. Soil nitrate-N (NO_3-N) and ammonia-N (NH_4-N) contents in the top 90 cm (0–30, 30–60 and 60–90 cm) samples of soil profile were collected before sowing and after maize harvest, respectively. Initial soil samples were collected in 0–20 cm to avoid any potential deficiency of other nutrients.

2.3. Experimental analysis

Plant sampling procedures followed the same standard for each experimental site. The sampling area (located within the middle part of the plot) was randomly selected in each treatment when harvest was used for determining grain yield. Ten well-proportioned maize plants were selected to determine moisture content, ultimately converted to a standard moisture content of 0.155 kg kg^{-1} H_2O for final grain yield. A separate three to five plant samples were selected to determine nutrient concentrations in grain and straw. All sub-samples including grain and straw were dried to constant weight at 70 °C for further nutrient analysis. Details for the analysis and calculation methods of nutrient concentration, nutrient uptake, AE_N, RE_N and gross profit were previously described by He et al. (2009) and PFP_N was previously described by Chuan et al. (2013b). Soil NO_3-N and NH_4-N contents in the fresh soil samples were extracted with 1:10 ratio of soil: 0.01 mol L $CaCl_2$ and analyzed using continuous flow analysis (Foss FIAstar 5000, Sweden). Soil water content was measured by oven drying at 105 °C. The ANOVA from PROC GLM of SAS software were performed with the differences between NE and FP.

We determined 'apparent N balance' to get an indication of the N dynamics in the soil such as N mineralization, apparent N losses, and residual N. Apparent N balance is also useful for estimating the environmental impact of a fertilizer recommendation. Apparent N mineralization and apparent N loss were estimated in our study using the following equations (Zhao et al., 2006):

$$\text{Apparent N mineralization}(N_{min}) = N_{uptake} + N_{residual} - N_{initial} \quad (1)$$

$$\text{Apparent N loss}(N_{loss}) = \text{Apparent N mineralization} + N_{fertilizer} + N_{initial} - N_{uptake} - N_{initial} \quad (2)$$

'Apparent N mineralization' was estimated in the control treatment whereas 'apparent N loss' was calculated in NE and FP treatments. N_{uptake} is N uptake by aboveground parts at harvest, $N_{residual}$ and $N_{initial}$ stand for the amount of inorganic N (NO_3-N and NH_4-N) in 0–90 cm soil layer after harvest and sowing, respectively, and $N_{fertilizer}$ is fertilizer N rate.

3. Results and discussion

3.1. Increasing yield and economic benefits of NE

Compared with FP, NE increased grain yields in six provinces except for SD province (the same yield (8.5 t ha^{-1}) was achieved for NE and FP in SD) (Table 2), increased by 1.2–6.1%. The yield of spring maize was higher than summer maize and the yield difference between NE and FP in spring maize (0.6 t ha^{-1}) was higher than summer maize (0.1 t ha^{-1}).

At each of the seven provinces except for HLJ province, the total fertilizer cost (TFC) in NE was less than that in FP (Table 2). On average, NE reduced TFC by US \$36 ha^{-1} compared with FP across all sites. Of these, NE saved US \$50 ha^{-1} for recommending less N with only US \$117 $ha^{-1}$for N fertilizer cost as compared to FP with US \$167 ha^{-1} for N fertilizer cost, and decreased US \$5 ha^{-1} for P fertilizer cost, and NE paid extra US \$19 ha^{-1} for increased K fertilizer cost. TFC was gradually increasing in FP with increasing fertilizer prices and the amount of fertilizer input. The higher TFC in spring maize than that in summer maize was due to the high P and K fertilizer input in spring maize (Table 3).

As price and grain yield increase for maize, the economics of producing maize improves. The average of gross return above fertilizer cost (GRF) in NE was US \$3049 ha^{-1} compared with US \$2928 ha^{-1} in FP (Table 2) across all sites, an increase with NE by US \$121 ha^{-1}. The important portion of increased profit was US \$85 ha^{-1} from more grain increases with NE than with FP. The higher GRF in spring maize than that in summer maize could be attributed to the higher grain yield in spring maize. The average GRF at each province with NE was higher than in FP, and the maximum increase in GRF (ΔGRF) was observed at LN, with an increase of US \$276 ha^{-1} (Table 2). The ΔGRF in spring maize was about triple of that in summer maize across all sites.

Fertilizer management in dose, space and time can significantly increase grain yield (He et al., 2009; Chen et al., 2011). Fertilizer recommendation and nutrient management based on NE fits in with the 4R nutrient stewardship strategy to optimize the supply and crop demand for nutrients and achieve balanced plant

Table 2
Effect of nutrient expert (NE) on grain yield and economic benefit at seven provinces in China (2010–2012).

	Grain yield (t ha^{-1})[a]				TFC (\$ ha^{-1})				GRF (\$ ha^{-1})			
Site[b]	NE	FP	Δ[c]	*P* > (T)[d]	NE	FP	Δ	*P* > (T)	NE	FP	Δ	*P* > (T)
HB	8.2	8.1	0.1	0.5207	236	241	−5	0.6294	2393	2371	22	0.4565
HN	9.8	9.6	0.2	0.0159	226	259	−33	<0.0001	2924	2842	82	0.0002
SD	8.5	8.5	0.0	0.4561	193	262	−69	<0.0001	2797	2688	109	<0.0001
SX	9.8	9.7	0.1	0.1033	242	244	−2	0.8750	3252	3219	33	0.0758
JL	12.1	11.8	0.3	0.0034	218	330	−112	<0.0001	3586	3359	227	<0.0001
LN	12.2	11.5	0.7	<0.0001	282	309	−27	0.0002	3946	3670	276	<0.0001
HLJ	11.1	10.6	0.5	<0.0001	288	278	11	0.1208	2817	2658	159	0.0001
All	10.1	9.9	0.2	<0.0001	236	272	−36	<0.0001	3049	2928	121	<0.0001
Spring	11.9	11.3	0.6	<0.0001	257	309	−52	<0.0001	3459	3239	220	<0.0001
Summer	9.2	9.1	0.1	0.0256	225	253	−28	<0.0001	2822	2756	66	<0.0001
2010	8.8	8.7	0.1	0.1710	193	229	−36	<0.0001	2458	2399	59	0.0019
2011	10.4	10.2	0.2	<0.0001	242	280	−38	<0.0001	3121	3006	115	<0.0001
2012	11.1	10.7	0.4	<0.0001	269	304	−35	<0.0001	3505	3320	185	<0.0001

[a] Grain yield for each province is average of three-year (2010–2012); TFC: total fertilizer cost; GRF: gross return above fertilizer cost; NE: Nutrient Expert; FP: farmers' fertilizer practice.
[b] Site: Hebei (HB), Henan (HN), Shandong (SD), Shanxi (SX), Jilin (JL), Liaoning (LN), and Heilongjiang (HLJ) provinces in China; all seven provinces from 2010 to 2012, the vales are average of three-year at all sites; spring: spring maize; summer: summer maize; 2010: 2010 spring and summer maize; 2011: 2011 spring and summer maize; 2012: 2012 spring and summer maize.
[c] Δ: NE–FP.
[d] *P* > (T): probability of a significant mean difference between NE and FP (1\$ = 6.2RMB).

Table 3
Effect of nutrient expert (NE) on fertilizer use at seven provinces in China (2010–2012).

	N fertilizer rate (kg ha^{-1})[a]				P_2O_5 application rate (kg ha^{-1})				K_2O application rate (kg ha^{-1})			
Site[b]	NE	FP	Δ[c]	P > (T)[d]	NE	FP	Δ	P > (T)	NE	FP	Δ	P > (T)
HB	153	266	−113	<0.0001	56	23	33	<0.0001	64	21	43	<0.0001
HN	157	213	−56	<0.0001	55	70	−15	0.0115	71	50	21	<0.0001
SD	143	233	−90	<0.0001	52	55	−3	0.4875	56	52	4	0.2855
SX	162	245	−83	<0.0001	50	31	19	0.0017	57	19	38	<0.0001
JL	149	211	−62	<0.0001	56	107	−51	<0.0001	67	91	−24	<0.0001
LN	178	229	−51	<0.0001	63	76	−13	<0.0001	79	48	31	<0.0001
HLJ	161	179	−18	0.0015	58	63	−5	0.1277	79	51	27	<0.0001
All	156	224	−68	<0.0001	55	62	−7	0.0035	68	49	19	<0.0001
Spring	161	207	−46	<0.0001	59	85	−26	<0.0001	74	67	7	0.0241
Summer	154	234	−80	<0.0001	54	50	4	0.2599	64	39	25	<0.0001
2010	138	223	−85	<0.0001	50	53	−3	0.5612	64	40	24	<0.0001
2011	162	220	−58	<0.0001	53	65	−12	0.0009	64	45	19	<0.0001
2012	167	231	−64	<0.0001	64	68	−4	0.2587	75	59	16	<0.0001

[a] Fertilizer application rate for each province are average of three-year (2010–2012), NE: nutrient expert; FP: farmers' fertilizer practice.
[b] Site: Hebei (HB), Henan (HN), Shandong (SD), Shanxi (SX), Jilin (JL), Liaoning (LN), and Heilongjiang (HLJ) provinces in China; all seven provinces from 2010 to 2012, the vales are average of three-year at all sites; Spring: spring maize; Summer: summer 2010: 2010 spring and summer 2011: 2011 spring and summer 2012: 2012 spring and summer maize.
[c] Δ: NE–FP.
[d] $P > (T)$: probability of a significant mean difference between NE and FP.

nutrition (Buresh, 2009; Dobermann and White, 1998; Dobermann and Witt, 2004). Compared to FP, NE increased grain yield and gross return above fertilizer cost, and decreased total fertilizer cost. Three-year field experimental results showed a 0.2 t ha^{-1} grain yield increase with NE (10.1 t ha^{-1}) over FP (9.9 t ha^{-1}). The low yield difference between NE and FP in summer maize was related to high soil indigenous nutrient supply due to excessive fertilizer application in the previous crops in FP and thus led to the lower yield response (Cui et al., 2008a). The one-time fertilizer application practice for farmers also has led to N deficiency in the late growth stage for spring maize. Grain yield was higher in spring maize than in summer maize, which could be due to the longer growth duration and the higher effective accumulated temperature. The high yield and low fertilizer would inevitably increase economic benefit with NE compared to with FP.

3.2. Fertilizer saving

NE method provides several fertilizer recommendations according to varying target yields and climates, such as spring and summer maize, and irrigation and rainfed maize. The user can select the yield and rainfall best matching their situation, such as soil types, water availability, flooding and drought problems, and soil-related problems (acidity and saline soils etc) and soil characteristics (soil depth, texture, color and organic matter content, and application of manure or compost). For example, N rates and times can be adjusted with in-season water condition, sometimes if there is no rain at the time of topdressing, N application can be delayed at a later season or otherwise not required. However, fertilizer application in the FP was very imbalanced in our study. On average, fertilizer N was greatly higher in the FP ranging from 179 to 266 kg ha^{-1} with an average of 224 kg ha^{-1} N across seven provinces. Fertilizer N application rate among 328 out of the total 408 experimental sites had higher than 180 kg N ha^{-1} in the FP treatment, accounting for 80.4% of all sites. In addition, the maximum N rate was 460 kg N ha^{-1} in 2010 at HB province, while the minimum was only 48 kg N ha^{-1} in 2010 at HN province. However, the optimized fertilizer N rate in the NE ranged from 143 to 178 kg ha^{-1} with an average of 156 kg ha^{-1} (Table 3). Fertilizer N in NE was significantly lowered by 30.4% (68 kg ha^{-1}, $P < 0.0001$) than FP. The difference in the N rates among years was due to the fact that NE approach is a dynamic nutrient management method, adjusting the amount of fertilizer according to residual N from previous crop, soil indigenous nutrient supply, the relationship between grain yield and nutrient uptake, yield response and agronomic efficiency (Chuan et al., 2013b).

Fertilizer P application in the FP ranged from 23 to 107 kg P_2O_5 ha^{-1} with an average of 62 kg P_2O_5 ha^{-1} compared with NE, which ranged from 50 to 63 kg P_2O_5 ha^{-1} with an average of 55 kg P_2O_5 ha^{-1}. Across all sites, however, there were 92 (22.5%) farmers who did not apply P fertilizer and for 179 (43.9%) farmers P fertilizer application rates had exceeded 70 kg P_2O_5 ha^{-1}. The maximum rate was 252 kg P_2O_5 ha^{-1} at HN province in the FP treatment in 2011, which far exceeded the P requirement of crop. On average, P fertilizer application in NE was lowered by 7 kg P_2O_5 ha^{-1} than in FP (11.3%, $P < 0.0001$).

Average K application rates in FP at seven provinces ranged from 19 to 91 kg K_2O ha^{-1} with an overall average of 49 kg K_2O ha^{-1} compared with NE, which ranged from 56 to 79 kg K_2O ha^{-1} with an overall average of 68 kg K_2O ha^{-1}. There were 190 farmers (FP), accounting for 46.6% of all sites, with K fertilizer application less than 45 kg K_2O ha^{-1}, of these, 121 farmers did not apply any K fertilizer. Across all sites, K fertilizer application rate in NE was significantly higher than in FP, with an increase of 19 kg K_2O ha^{-1} (38.8%, $P < 0.0001$, Table 3).

Indigenous nutrient supply needs to be considered in developing fertilizer recommendations (Dobermann et al., 2003a; Khurana et al., 2007), because over-fertilization are very common for farmers' practices in China and has led to the higher indigenous nutrient supply in the soil (Cui et al., 2008b), and has made up potential threat to the environment security. Indigenous nutrient supply comes from soil mineralization, irrigation water, atmospheric deposition, rainfall, previous crop residues, and nutrient fixed by legumes and bacteria, and can be measured in nutrient omission plots (Dobermann et al., 2003b). High indigenous nutrient supply indicates that large amount of nutrients remained in the soil, and fertilizer resources are not used effectively, this could lead to soil and fertilizer nutrients loss and eventually into the surface water, groundwater and air through leaching, runoff, volatilization and denitrification, etc (Ju et al., 2009). The NE method enabling farmers to dynamically adjust fertilizer application rates based on crop requirements, which adjusts fertilizer rates based on yield response, agronomic efficiency and nutrient balance for every year or season rather than using a constant

Table 4
Effect of Nutrient Expert (NE) on N use efficiency at seven provinces in China (2010–2012).

Site[b]	AE_N (kg grain kg^{-1} N)[a]				RE_N (%)				PFP_N (kg grain kg^{-1} N)			
	NE	FP	Δ[c]	P > (T)[d]	NE	FP	Δ	P > (T)	NE	FP	Δ	P > (T)
HB	6.6	3.7	2.9	<0.0001	22.1	11.3	10.8	<0.0001	54.3	32.1	22.2	<0.0001
HN	14.1	10.5	3.6	<0.0001	35.4	23.5	11.9	<0.0001	64.0	51.7	12.3	<0.0001
SD	8.3	5.6	2.7	<0.0001	20.9	14.0	6.9	<0.0001	59.9	39.4	20.5	<0.0001
SX	7.8	5.5	2.3	<0.0001	25.4	16.9	8.5	<0.0001	61.9	44.3	17.6	<0.0001
JL	15.5	9.5	6.0	<0.0001	35.2	26.9	8.3	<0.0001	82.5	59.1	23.4	<0.0001
LN	13.1	7.1	6.0	<0.0001	34.6	16.3	18.3	<0.0001	69.5	50.5	19.0	<0.0001
HLJ	18.9	14.3	4.6	<0.0001	32.5	26.5	6.0	<0.0001	69.3	61.2	8.1	<0.0001
All	12.2	8.3	3.9	<0.0001	30.2	20.0	10.2	<0.0001	65.7	48.5	17.2	<0.0001
Spring	15.8	10.2	5.6	<0.0001	34.2	23.8	10.4	<0.0001	74.9	57.3	17.6	<0.0001
Summer	10.3	7.2	3.1	<0.0001	28.0	17.8	10.2	<0.0001	60.6	43.6	17.0	<0.0001
2010	12.6	8.7	3.9	<0.0001	30.0	18.5	11.5	<0.0001	64.4	45.5	18.9	<0.0001
2011	12.3	8.6	3.7	<0.0001	31.6	22.2	9.4	<0.0001	64.8	49.7	15.1	<0.0001
2012	11.9	7.6	4.3	<0.0001	29.0	18.6	10.4	<0.0001	67.9	49.7	18.2	<0.0001

[a] N use efficiency for each province are average of three-year (2010–2012); AE_N: agronomic efficiency of applied N; RE_N: apparent recovery of applied N; PFP_N: partial factor productivity of applied N; NE: Nutrient Expert; FP = farmers' fertilizer practice.
[b] Site: Hebei (HB), Henan (HN), Shandong (SD), Shanxi (SX), Jilin (JL), Liaoning (LN), and Heilongjiang (HLJ) provinces in China; all seven provinces from 2010 to 2012, the vales are average of three-year at all sites; spring: spring maize; summer: summer 2010: 2010 spring and summer 2011: 2011 spring and summer 2012: 2012 spring and summer maize.
[c] Δ: NE–FP.
[d] P > (T): probability of a significant mean difference between NE and FP.

fertilizer rate. The differences in climatic conditions suggested that different nutrient management strategies were required for managing maize in each domain, which is one of the main considerations of the NE method.

3.3. Increasing fertilizer use efficiency

In order to decrease fertilizer apparent N loss to the environment, fertilizer use efficiency should be increased maximally in fertilizer recommendation and nutrient management. N use efficiencies achieved in NE were significantly increased compared with FP. AE_N in NE ranged from 6.6 to 18.9 kg kg^{-1} with an average of 12.2 kg kg^{-1}, RE_N ranged from 20.9% to 35.4% with an average of 30.2%, PFP_N ranged from 54.3 to 82.5 kg kg^{-1} with an average of 65.7 kg kg^{-1}. In FP, AE_N ranged from 3.7 to 14.3 kg kg^{-1} with an average of 8.3 kg kg^{-1}, RE_N form 11.3% to 26.9% with an average of 20.0%, and PFP_N from 32.1 to 61.2 kg kg^{-1} with an average of 48.5 kg kg^{-1} (Table 4). On average, AE_N, RE_N and PFP_N with NE were increased by 3.9 kg kg^{-1} (47.0%), 10.2% (51.0%), and17.2 kg kg^{-1} (35.5%) compared with FP, respectively (Table 4). Across seven provinces, AE_N in NE was higher by more than 30% compared with FP. Generally, the single basal fertilizer application for farmers leads to excessive N supply during early vegetative growth but deficiency during grain filling, especially for spring maize. While with NE, several questions related to environments like water availability, flooding and drought problems, and soil-related problems such as acidity and saline soils are embedded into NE software to estimate attainable yield and yield response. Fertilizer recommendation is also given based on in-season weather condition, fertilizer N is applied two to three times according to the nutrient demand of crop at critical growth stages, and the second or third time of N splitting will be adjusted if no rain forecasted in the coming season. The results from farmers' practices indicated that high N fertilizer rates did not result to higher N use efficiency. N use efficiencies was higher in spring maize than that in summer maize, these may be related to the long growth duration and high effective accumulated temperatures for spring maize growing regions, which can improve fertilizer nutrient uptake and effectively transfer to crop reproductive organs.

The average AE_N obtained by NE from our study was 12.2 kg, higher than soil testing and farmers' practices with 9.8 kg and 8.3 kg, respectively (Xu et al., 2014). Also the AE_N from this NE field validation was higher than most of other study from soil testing fertilizer recommendation (He et al., 2009). As compared with report from Dobermann (2007), AE_N could be reached to 20–30 kg under low N application rate or optimal management including optimum nutrient management, irrigation, high-yielding variety, weeds, pests and diseases control, etc. The low AE_N currently in China (Cui et al., 2009; Gao et al., 2012), is due to the poor management in the field, and it is possible to reach to a higher AE_N with under the best management practices with the development of agricultural technology such as precision agriculture, and mechanization in the future. The AE_N from our current study have reach to 20–30 kg in some of our experimental sites in Heilongjiang Province. However, the greater fertilizer applied in the preceding crops resulted in the higher initial N in the soil before sowing maize (Table 5). The high initial N accumulation, high fertilizer N application, improper nutrient management, and nutrient imbalance (many farmers applied only N and P or only N fertilizer) have led to low nutrient use efficiency for farmers' practices.

3.4. Reducing apparent N loss

The results gave a slight increase (0.2 t ha^{-1}) in crop yield compared with FP and significant differences ($P < 0.0001$) was found across all sites. It was indicated that, however, high yields could be achieved with lower N fertilizer rates. In contrast, total

Table 5
Nitrogen balances in nutrient expert (NE) and farmers' fertilizer practice (FP) treatments after harvest in 2012.

Item[a]	Summer maize (n = 33)		Spring maize (n = 62)	
	NE[b]	FP	NE	FP
$N_{initial}$ (kg ha^{-1})	209.7	207.6	166.9	166.9
N_{min} (kg ha^{-1})	139.1	141.2	73.6	73.6
$N_{fertilizer}$ (kg ha^{-1})	179.3	239.2	161.5	218.4
N_{uptake} (kg ha^{-1})	226.5	212.5	201.8	187.7
$N_{residual}$ (kg ha^{-1})	226.1	268.4	126.1	147.6
N_{loss} (kg ha^{-1})	85.6	107.1	74.0	123.7
Grain yield (t ha^{-1})	10.4	10.3	12.2	11.5

[a] $N_{initial}$: residual NO_3-N and NH_4-N in 0–90 cm soil depth before sowing; N_{min}: apparent N mineralization; $N_{fertilizer}$: fertilizer rate; N_{uptake}:N uptake by above-ground parts at harvest; $N_{residual}$: residual NO_3-N and NH_4-N in 0–90 cm soil depth after harvest; N_{loss}: apparent N loss.
[b] NE: nutrient expert; FP: farmers' fertilizer practice.

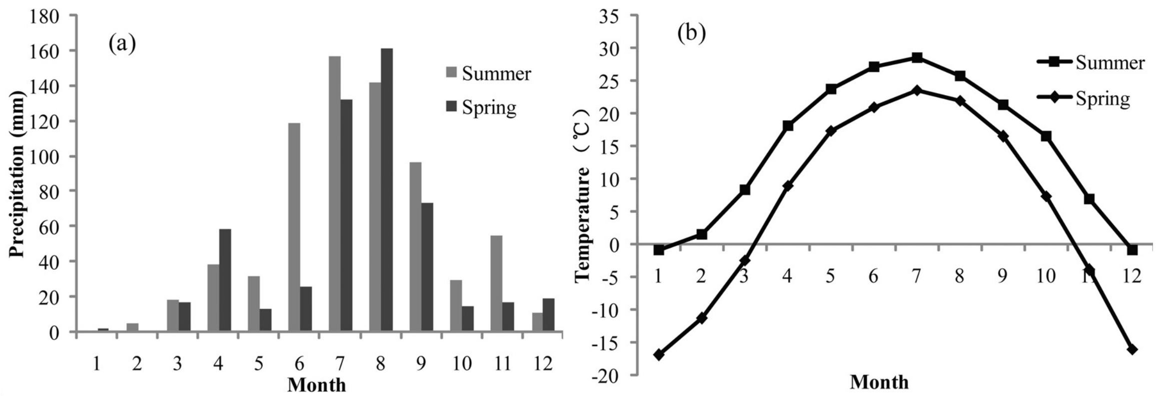

Fig. 2. Monthly rainfall (mm) and mean temperature (°C) in the field experiments for summer maize and spring maize in 2012.

apparent N losses increased significantly with increasing N inputs, indicating high environmental costs were caused by exceeding optimum N fertilizer rates. For summer maize, N fertilizer application in NE (179.3 kg ha^{-1}) was lower than in FP (239.2 kg ha^{-1}), but N uptake in NE (226.5 kg ha^{-1}) was high than in FP (212.5 kg ha^{-1}), and soil residual N were 209.7 and 207.6 kg ha^{-1} before planting, and 226.1 and 268.4 kg ha^{-1} at harvest in NE and FP treatments, respectively. However, apparent N loss was lower in NE (85.6 kg N ha^{-1}) than in FP (107.1 kg N ha^{-1}). For spring maize, N fertilizer application in NE (161.5) was also lower than in FP (218.4), while N uptake in aboveground dry matter was higher in NE (201.8) than in FP (187.7). Soil residual N at harvest in NE (126.1 kg ha^{-1}) and FP (147.6 kg ha^{-1}) were lower than the initial N (166.9 kg ha^{-1}) measured before sowing. However, there was still substantial amount of apparent N loss for both NE (74.0 kg ha^{-1}) and FP (123.7 kg ha^{-1}) (Table 5). With this NE based fertilizer recommendation, N fertilizer reduced by 68 kg/ha (30.4%) and 47 kg/ha (23.3%) as compared with farmers practice and soil testing, while maintaining higher grain yield and profitability, which is of great contribution to fertilizer N saving and apparent N loss currently in China (Xu et al., 2014). Therefore, NE has the advantages over both soil testing and farmer practice, while NE will optimize further based on the improvement of nutrient management practices.

N loss to the environment would increase when fertilizer rate exceeding the optimum rate of the crop requirements. Successive high N fertilizer application has led to high indigenous nutrient supply and N accumulation in the soil and posing a threat to the environment (Ju et al., 2009; Cui et al., 2008a), these nutrients through leaching can seep into groundwater and polluting rivers and lakes. The high residual N accumulation was found in the soil profile and gradual leaching below the root zone was the important N loss pathway for summer maize (Ju et al., 2009). Ammonia volatilization was regarded to be the another major pathway of N loss for summer maize growing season due to the relative high pH (Table 1), high temperature in growing season (Fig. 2) and used urea or ammonium salt as fertilizer which usually was surface application. The other ways such as the flood irrigation and the concentrated rainfall (Fig. 2) were also the reasons for apparent N loss. Nevertheless, the most important cause for apparent N loss is the continuous excessive N fertilizer application for farmers' practices. Many of farmers still believe the traditional opinions that higher crop yield obtained need more fertilizer.

Total N losses including NH_3 volatilization, denitrification and leaching from the soil profile increased significantly with increasing N inputs, indicating high environmental costs were caused by high fertilizer application exceeding crops N requirements. Making full advantage of residual soil N could improve nitrogen use efficiency and help estimate optimum N fertilizer rates for maize (Setiyono et al., 2011; Chen et al., 2010). There was the high potential N supplying capacity in the soil which include apparent N mineralization and the high initial N (NO_3-N +NH_4-N) accumulation at 0–90 cm depth in the soil profile, and N from atmospheric and irrigation water. There was the high N mineralization for summer maize (139.1 kg ha^{-1} in NE and 141.2 kg ha^{-1} in FP) compared to spring maize (73.6 kg ha^{-1}). The high mineralization for summer maize may be related to the high accumulation of nitrate in soils (Cui et al., 2008a). Environmental N input must be considered in the fertilizer recommendation due to total environmental N inputs has been reached about 104 kg N of per hectare on the North China Plain (Ju et al., 2009). However, Nutrient Expert for Hybrid Maize takes soil nutrient supply as "black box" which can be supplied from soil mineralization, irrigation water, atmospheric deposition, rainfall, crop residues and biological fixation and so on, and was considered one of the important factors when making fertilizer recommendation (He et al., 2012; Pampolino et al., 2012; Chuan et al., 2013b). So, NE method gives optimum N according to specific field conditions, with taking into consideration climate, soil and management.

4. Conclusions

A good fertilizer recommendation method should focus on not only maintaining high crop yield, but also reducing environmental risks so as to maintain sustainable development of agriculture. Compared with FP, proper fertilization dosage and fertilizer application time based on NE increased fertilizer K rate, and reduced N and P fertilizer rates, which significantly increased grain yield, plant nutrient uptake, nutrient use efficiency, economic benefits, and reduced apparent N loss. The NE method is a dynamic fertilization model, which adjusts fertilizer rates based on yield response, agronomic efficiency and nutrient balance for every year or season rather than using a constant fertilizer rate. The difference in climate conditions suggested that different nutrient management strategies were required for managing maize in each domain, which is one of the main considerations of the NE method. The NE method provides a scientific and reasonable guidance for fertilizer recommendation and nutrient management, enabling farmers to dynamically adjust fertilizer application rates based on crop requirements. The results of a three-year field experiment (408 farmers) suggested that NE is a rational, reliable and practical method for small-holder maize farms in China.

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