Evaluation of a new fertilizer recommendation approach to improve nitrogen use efficiency across small-holder farms in China

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Abstract
Low fertilizer use efficiency caused by over and imbalanced fertilization is the great challenge in intensified agricultural production systems in China. Therefore, it is necessary to develop a better nutrient management and fertilizer recommendation approach for small-holder farms in China. This paper introduces a new fertilizer recommendation approach based on yield response and agronomic efficiency, which addresses all such concerns. The nutrient management principles were developed to consolidate the complex and knowledge intensive information into simple deliverable computer software named "Nutrient Expert" enabling local advisors rapidly implement this technology to ensure field specific guidelines for fertilizer recommendations. The software only requires information that can be easily provided by farmers or local expert. The user will get a guideline on fertilizer management (and more, such as recommended plant density, attainable yield, profit analysis, etc) that are tailored to his location and locally available fertilizer sources after answering a set of simple questions. Nutrient Expert advocates managing the 4R Nutrient Stewardship strategy adopted by the global fertilizer industry compatible with the economic, social and environmental goal of sustainable development. Multiple-site field validation demonstrated that the easily grasped new approach based on yield response and agronomic efficiency helps in strategizing appropriate management of nutrients leading to better yield, nitrogen use efficiency and environmental sustainability.

Key Words
Crop yield response, agronomic efficiency, Nutrient Expert, 4R nutrient stewardship, fertilizer recommendation

Introduction
Over and imbalanced fertilization in intensified farmland in China results in low fertilizer use efficiency, and thus effects sustainable development of farmland. Therefore, it is in great need to develop a better nutrient management and fertilizer recommendation approach for smallholders in China. Previous studies on fertilizer recommendation mainly focused on two categories, soil based and plant based fertilizer recommendation. Fertilizer recommendation based on soil testing and yield targets has been reported to increase yield for the wheat–maize cropping system in North-central China (He et al., 2009). However, it is expensive and time consuming to take numerous soil samples for smallholder farmers with great variation due to variation in individual fertilization patterns (Huang et al., 2006). In addition, the great challenge for North Central and South China is the limited interval between the two crop seasons rotated in a year. The crop based fertilizer recommendation needs to estimate crop nutrient uptake to balance crop removal for a certain grain yield target. Previous studies used for crop nutrient estimation usually used a single value summarized from few data for large areas, which at times could make fertilizer recommendations misleading. Most of the nutrient management in the past usually ignored the interactions of plant nutrients and only addressed a single nutrient. A new fertilizer recommendation approach, Nutrient Expert (NE), developed by the International Plant Nutrition Institute (IPNI) and Chinese Academy of Agricultural Sciences (CAAS) considered the site specific nutrient management (SSNM) which has been used to more closely match nutrient demand and supply within a specific field in a particular cropping system, and proved to obtain high crop yield and high nutrient use efficiency (Chuan et al., 2013a, 2013b; Xu et al., 2013, 2014a, 2014b, 2015), and to protect the environment (Pampolino et al., 2007). However, no information is available on long-term sustainability of the NE system on grain yield and nitrogen use efficiency. The aim of this study is to evaluate whether the NE system could maintain grain yield and improve the N-use efficiency through three-year fixed site experiments.

Methods

Analysis of N efficiency and GHG emission

The Hybrid-Maize model was used to make fertilizer recommendation for each field validation for all locations at Jilin and Heilongjiang provinces during 2012–2014.The straw and grain sample were collected to analyze N, P and K concentration. The total nutrient uptake, nutrient use efficiency including recovery efficiency of N (REN), partial factor productivity of N (PFPN), and agronomic efficiency of N (AEN) of nutrient application were calculated based on our previous publication (Xu et al., 2015). We also calculated the direct N_2O emissions and indirect N_2O emissions including ammonia (NH_3) volatilization and nitrate (NO_3^{-1}) leaching for spring maize according to Zhao et al (2016). The ANOVA analysis from SPSS 13.0 software were performed on the differences among NE, FP and OPTS at 0.05 level.

Nutrient Expert for Hybrid maize

The Nutrient Expert (NE) is a computer software which consolidates the complex and knowledge intensive information into simple deliverable tool enabling local advisors rapidly implement this technology to ensure field specific guidelines for fertilizer recommendations. The software only requires information that can be easily provided by farmers or local expert. The core of the fertilizer recommendation method in Nutrient Expert is based on yield response and agronomic efficiency (AE). The yield response to fertilizer N, P and K is the yield gap between NPK plots that receive ample nutrients and omission plots when one of the nutrients is omitted. The agronomic efficiency of fertilizer N, P, and K are the yield increase per unit of fertilizer nutrient applied. The determination of fertilizer N requirement from Nutrient Expert for Expert for Hybrid maize has been modified to use an estimation of yield response and a target agronomic efficiency of applied N. The determination of fertilizer P and K in the NE system considers the internal nutrient efficiency combined with estimate of attainable yield, nutrient balance and yield responses within specific field (Pampolino et al., 2012; Chuan et al., 2013b). Secondary and micronutrient recommendation are mainly based on soil testing which is integrated into the NE system. The Nutrient Expert advocates managing the 4R Nutrient Stewardship strategy adopted by the global fertilizer industry. 4R is an approach to managing the right source, rate, timing and placement of fertilizer nutrients in a cropping system.

On-farm research approach

On-farm experiments were conducted in the major maize production zones of Northeast China (latitude 39.05-53.53 ° N, longitude 118.86-135.07 ° E), to develop and evaluate the NE system. A total of 20 on-farm location experiments were selected from the 2012 experiments and were conducted between 2012 and 2014, to validate the effects of NE use by examining the yield, agronomic and environmental performance of each site. The experiments were located in the Jilin and Heilongjiang provinces of Northeast China.

All on-farm experiments followed a standardized experimental protocol. Six treatments were set for each experiment to compare the NE recommendation, farmers' practice (FP), and soil testing (OPTS) results, and a series of nutrient omission plots, which excluded N, P or K from the NE treatment.

Results

Grain yield

In all sites and years, the NE treatment obtained highest grain yield, which was significantly higher than the FP treatment in all sites/years, but not significantly different from the OPTS treatment (Figure 1). For the FP treatment, the farmers applied 16.4% (13.5%-20.3%) more N than the NE treatment, but could not achieve higher yield due to single application. No differences existed between the NE and OPTS treatments due to not much differences in fertilizer application quantity (Table 1). The NE treatment demonstrated advantages in N splitting and balancing K over the FP treatment.

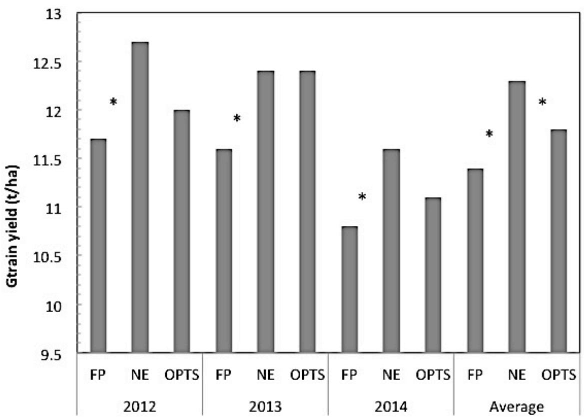

Figure 1. Grain yields for the Nutrient Expert (NE), farmers' practices (FP) and soil testing (OPTS) in 2012, 2013 and 2014.

N use efficiency parameters

The recovery efficiency (RE), agronomic efficiency (AE), and partial factor productivity (PFP) of applied N are frequently used in agronomic research to assess the N use efficiency (Cassman et al., 2002; Dobermann, 2007; Snyder and Bruulsema, 2007). The NE treatment had considerably higher N use efficiency than the FP treatment for each year (Table 1). On an average, the REN, AEN and PFPN under the NE treatment were significantly higher than in the FP treatment ($P<0.001$), showing increases of 12%, 6 kg/kg, and 14 kg/kg, respectively. In the NE treatment, REN, AEN and PFPN were also higher than found in the OPTS treatment, and was higher by 4%, 1 kg/kg and 4 kg/kg, respectively. The AEN and PFPN in the NE treatment were 6 kg/kg and 11 kg/kg higher, respectively than those obtained by Gao et al. (2012), in Northeast China.

Table 1. Fertilizer application rate and nitrogen use efficiency of for the Nutrient Expert (NE), farmers' practices (FP) and soil testing (OPTS) in 2012, 2013 and 2014.

Year	Treatment	Fertilizer rate (kg/ha)			REN	AEN	PFPN
		N	P	K	(%)	(kg/kg)	(kg/kg)
2012	NE	165 b[a]	26 b	65ab	33 a	18 a	77 a
	FP	207 a	40 a	61 b	21 b	11 b	59 b
	OPTS	167 b	27 b	73 a	30 a	17 a	73 a
2013	NE	175 b	36ab	73 a	33 a	19 a	71 a
	FP	207 a	40 a	61 b	22 b	13 b	59 b
	OPTS	186 b	28 b	68ab	30 a	19 a	67 a
2014	NE	179 b	34ab	71 a	39 a	21 a	66 a
	FP	207 a	40 a	61 a	27 c	14 c	53 b
	OPTS	186 b	28 b	68 a	32 b	17 b	61 a
Average	NE	173 b	32 b	69 a	35 a	19 a	71 a
	FP	207 a	40 a	61 b	23 c	13 b	57 b
	OPTS	179 b	28 b	70 a	31 b	18 a	67 a

[a] The comparisons are within columns among NE, FP and OPTS in 2012, 2013, 2014 and the average 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.

Apparent N loss and GHG emissions

Three years of results indicated that use of NE produced a high yield with low environmental pollution, compared with the FP treatment (Table 2). Based on the three-year total calculated N balance, N fertilizer application under the NE treatment (519 kg/ha) was lower than under the FP treatment (622 kg/ha), but N uptake in the above-ground under the NE treatment (569 kg/ha) was 39 kg N/ha greater than that under the FP treatment (530 kg/ha). 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 kg/ha) was significantly lower ($P<0.001$) than that under the FP treatment (149 kg/ha), representing a decrease of 63 kg/ha.

The three-year total GHG emissions under the NE treatment would decrease by 17%, from 8849 to 7359 kg CO_2eq/ha, compared with the FP treatment (Table 2). 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 kg CO_2eq/t grain). Relative to the OPTS treatment, the NE treatment not only saved N fertilizer (19 kg N/ha) and increased N uptake (15 kg N/ha), but also reduced residual N at harvest (27 kg/ha). Furthermore, total GHG emissions and GHG emission intensity decreased by 240 kg CO_2 eq/ha, and 15 kg CO_2 eq/t grain, respectively.

Conclusion

Our work with NE has clearly demonstrated that we can use this tool to help make the best choices in fertilizer management, which fit in with the 4R Nutrient Stewardship strategy, specifically to study the right fertilizer rate and the right fertilizer application time. The NE based fertilizer recommendation can not only maintain the better grain yield, but also improve the agronomic efficiency, recovery efficiency and partial factor productivity of N and lower GHG emission than those in FP and soil testing. It was demonstrated that the NE is a promising fertilizer recommendation method that can improve grain yield and nutrient efficiency and protect the environment, and can be used without soil testing.

Table 2. 5 Nitrogen balances and greenhouse gas (GHG) emissions for nutrient expert (NE), famers' 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
$N_{initial}$ (kg ha^{-1})	177	177	177
Total $N_{fertilizer}$ (kg ha^{-1})	519	622	538
Total N_{uptake} (kg ha^{-1})	569	530	554
$N_{residual}$ (kg ha^{-1})	86	149	113
Total GHG emissions (kg CO_2eq ha^{-1})	7359	8849	7599
GHG emission intensity (kg CO_2eq t^{-1} grain)	203	262	218

$N_{initial}$: residual NO_3–N and NH_4–N in 0–90 cm soil depth before sowing in 2012; $N_{fertilizer}$: N 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 in 2014.

References

Cassman, K.G., A. Dobermann, and D.T, Walters. 2002. Agroecosystems, nitrogen-use efficiency, and nitrogen management. Ambio 31(2):132-140.

Chuan, L.M., He, P., Jin, J.Y., Li, S.T., Grant, C., Xu, X.P., Qiu, S.J., Zhao, S.C., Zhou, W. 2013a. Estimating nutrient uptake requirements for wheat in China. Field Crops Research, 146, 96-104

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. 2013b. Establishing a scientific basis for fertilizer recommendations for wheat in China: Yield response and agronomic efficiency. Field Crops Research. 140,1-8

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.

Huang, S.W., Jin, J.Y., Yang, L.P., Bai, Y.L. 2006. Spatial variability of soil nutrients and influencing factors in a vegetable production area of Hebei province in China. Nutrient Cycling in Agroecosystems. 75, 201-212

Dobermann, A., 2007.Nutrient use efficiency – measurement and management. In Krauss, A., et al. (Eds) Fertilizer Best Management Practice: General Principles, Strategy for their Adoption and Voluntary Initiatives vs Regulations. IFA Int. Worksh. on Fertilizer Best Management Practices, Brussels, Belgium. 7-9 March 2007, Int. Fert. Ind. Assoc., Paris, France., 1–28.

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. Agr. 88, 103–110.

Snyder, C.S., and T.W. Bruulsema. 2007. Nutrient use efficiency and effectiveness in North America: Indices of agronomic and environmental benefit. Reference # 07076. Norcross, GA: International Plant Nutrition Institute.

Qiu, S.J., He, P., Zhao, S.C., Li, W.J., Xie, J.G., Hou, Y.P., Grant, C.A., Zhou, W., Jin, J.Y. 2015. Nitrogen rate influences on nitrogen partitioning and efficiency parameters in Northeast China rain-fed maize production systems. Agronomy Journal, 107,1-9

Xu, X.P., He, P., Pampolino, M.F., Chuan, L.M., Johnston, A.M., Qiu, S.J., Zhao, S.C., Zhou, W., 2013. Nutrient requirements for maize in China based on QUEFTS analysis. Field Crops Res. 150, 115–125.

Xu, X.P., He, P., Pampolino, M.F., Johnston, A.M., Qiu, S.J., Zhao, S.C., Chuan, L.M., Zhou, W., 2014b. Fertilizer recommendation for maize in China based on yield response and agronomic efficiency. Field Crops Res. 157, 27–34.

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

Xu, X.P., Liu X.Y., He, P., Johnston, A.M., Zhao, Zhao, S.C., Qiu, S.J., Zhou, W., 2015. Yield gap, indigenous nutrient supply and nutrient use efficient for maize in China. Plos One10, 1–12.

Zhao, S.C., He, P., Qiu, S.J., Jia, L.L., Liu, M.C., Jin, J.Y., Johnston, A.M. 2014. Long-term effects of potassium fertilization and straw return on soil potassium levels and crop yields in north-central China. Field Crops Research, 169,116-122

Zhao, S.C., Qiu, S.J., Cao, C.Y., Zheng, .CL., Zhou, W., He, P. 2014. Responses of soil properties, microbial community and crop yields to various rates of nitrogen fertilization in a wheat-maize cropping system in north-central China. Agriculture, Ecosystems and Environment, 194,29-37.

Zhao, R.R., He, P., Xie, J.G., Johnston, A.M., Xu, X.P., Qiu, S.J., Zhao, S.C. 2016. Ecological Intensification Management of Maize in Northeast China: Agronomic and Environmental response. Agriculture, Ecosystems and Environment, 224,123-130.