Evaluation of Nutrient Expert system in improving nutrient use efficiency and environmental benefits for winter wheat in the Hebei Plain

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Abstract. This research evaluates the nutrient management system of Nutrient Expert (NE) in winter wheat grain yield production and greenhouse gas (GHG) emission in the Hebei Plain. Field experiments were conducted to check the yield effects, nutrient use efficiency (NUE) and GHG under NE (nutrient management based on Nutrient Expert recommendation) and FP (nutrient management based on farmers’ practices). The results showed that NE significantly reduced N fertilizer input while maintain higher yield and nutrient use efficiency than FP. The total N\textsubscript{2}O emission and GHG emissions for NE were about 0.69 kg N ha\textsuperscript{-1} and 1686 kg CO\textsubscript{2} eq ha\textsuperscript{-1} respectively, significantly lower than for FP (p<0.05), which was about 1.85 kg N ha\textsuperscript{-1} and 3329 kg CO\textsubscript{2} eq ha\textsuperscript{-1}, respectively. The NE system showed great potential to be easily used in smallholder farmers in the Hebei Plain.

1. Introduction
Winter wheat is one of the most important crops in the Hebei Plain (HBP). The total cultivation area of winter wheat in HBP was about 2.3×10\textsuperscript{6} hectares, and the yearly production was about 14.3×10\textsuperscript{6} tons, accounts for more than 9.7% of wheat cultivated land area and 11.0% wheat production in China in 2015 [1], therefore it plays a very important role for food security and increasing the farmer’s income in China. However, in order to get higher grain yield, excessive or imbalanced fertilization by smallholder farms in HBP has become very common [2-3]. Over fertilization can cause serious environment impacts, such as surface water eutrophication, ground water nitrate contamination and greenhouse gas emission [4-6]. The increasing environmental concern asked the optimizing nutrient management to improve grain yield and nutrients use efficiency (NUE) while maintaining the environment sound.

Multiple-point field experiments based on soil testing fertilization method or yield targets fertilization methods have been conducted and showed significant yield and NUE improvement in China [7]. However, the shortcomings for soil testing method be used in the HBP is too labor cost, expensive and time consuming. The soil testing fertilizer recommendation needs comprehensive field sampling and expensive laboratory analysis. Due to the great variations of fertilization history for different farmers, the soil testing fertilizer recommendation cannot be performed well in hundreds and millions of smallholder farmers’ fields [8]. Therefore, an easy use interface friendly nutrient management decision support tools, which can give suggestions to reducing nutrient inputs while maintaining high grain yield, improving NUE and mitigating GHG emissions is important for the smallholder farmers in the HBP.
In recent years, a new winter wheat fertilizer recommendation method named Nutrient Expert [9], which is based on yield response and agronomy efficiencies, has been developed and used in the North China Plain [10-11]. This method provides the ability of maintaining the crop yields while reducing the N fertilizer application rates, but few evaluations of the Nutrient Expert system on improving the winter wheat NUE and environmental benefits in HBP were conducted. In this context, we conducted multi-points on-farm experiments to study the long-term sustainability of Nutrient Expert for Winter Wheat in improving NUE and reducing the GHG emissions in the HBP. We compared the amount of fertilizer nitrogen, phosphate and postassium input rates, crop yield, NUE and GHG emissions between the Nutrient Expert (NE) and Farmers’ Practice (FP), and assessed the stability of NE fertilizer recommendation for grain yield increasing, NUE and reducing GHG emission intensity.

2. Materials and Methods

2.1. Experiment arrangement

These field trails were arranged in farmers’ fields in the HBP from 2010-2012. There were totally 43 field trials were conducted in Xinji County (XJ) in 2 crop seasons, and 8 field trails were conducted in ZhengDing County (ZD) in 2011-2012 crop season. These fields in this research are the typical loamy soil, which can represent the typical soil types and the local farmers’ agricultural management strategies. The warm temperate, sub-humid continental monsoon climate is the dominated climate type in this region. The main cropping system in this research is a wheat-maize rotation system, and winter wheat was planted in the beginning of October and was harvested in the beginning of June the next year. The wheat varieties were Jimai 22 and Shimai 15, which were popular in this region. All the plots received the same cultivation practices, such as seeding rate, irrigation rate, weed, pest and disease controls. All these cultivation practices were similar as the best local management practices as the local farmers.

Each experiment included 3 treatments of no any fertilizer input (CK, control), Nutrient Expert fertilizer recommendation (NE) and Farmers fertilization Practices (FP). Fertilization input rates of N, P2O5, K2O for NE were based on Nutrient Expert; FP fertilization rate was come from a survey of farmer’s fertilization rates in the last wheat season. The fertilizers used in this research were urea (N46%), Superphosphates (P2O5 46%), and potassium chloride (K2O, 60). The basal fertilizers including all the P and K fertilizers and 1/3 N fertilizer were applied before wheat sowing in the early October, the 2/3 of N fertilizer as topdressing was fertilized at shooting stage in the beginning of April the next year. The detailed fertilization rates for NE and FP treatments were listed in Table 1.

| Year       | Location | Sites | NE Recommended (kg ha⁻¹) | Farmers’ Practices (kg ha⁻¹) |
|------------|----------|-------|--------------------------|-------------------------------|
|            |          |       | N            | P2O5          | K2O          | N            | P2O5          | K2O          |
| 2010-2011  | XJ       | 31    | 135 (130-150) | 52 (50-56)  | 60 (48-70)  | 278 (196-344) | 42 (30-68)  | 24 (0-68)    |
| 2011-2012  | XJ       | 12    | 182 (182)    | 72 (67-79)  | 85 (80-105) | 346 (234-460) | 33 (0-113)  | 47 (0-158)   |
| 2011-2012  | ZD       | 8     | 182 (182)    | 76 (67-89)  | 76 (65-105) | 247 (218-266) | 47 (34-54)  | 53 (44-68)   |

*Notes: numbers in brackets are fertilization rates distribution range for NE and FP in different experiment sites.*
2.2. Plant sampling and management

For each treatment, plants from three separated 3 m² area of wheat plants in each plot were harvested manually, dry weights of stems and grains were determined after separation and oven-dried at 60°C. The partial factor productivity of applied N (PFPN), which is defined as the average productivity of nitrogen fertilizer application, was calculated to interpret the nutrient use efficiency. The equation of PFPN was as below:

$$\text{PFPN (kg kg}^{-1}\text{)} = \frac{Yf}{N \text{ input}}$$

where $Yf$ (kg ha⁻¹) is the grain yield in N application, and N input (kg ha⁻¹) is the fertilizer N input.

2.3. Estimation of GHG emission and emission intensity

In the whole life cycle of wheat production, the total GHG emissions include CO₂, CH₄ and N₂O (CH₄ emission was not calculated in this research). The detailed calculation method is listed as below [12-13]:

$$\text{GHG}_{\text{total}} = (\text{GHG}_{\text{m}} + \text{GHG}_{\text{i}}) \times \text{N rate} + \text{total N₂O} \times 44/28 \times 298 + \text{GHG}_{\text{others}}$$

where $\text{GHG}_{\text{total}}$ (kg CO₂ eq ha⁻¹) is the total greenhouse gas emissions in the whole life cycle of wheat production. The $\text{GHG}_{\text{m}}$ is the GHG emission in the process of industry’s energy source from the fossil mining to N products manufacturing. The $\text{GHG}_{\text{m}}$ is 8.21 kg CO₂ eq ha⁻¹ [14]. The $\text{GHG}_{\text{i}}$ is the transportation emission factor for nitrogen fertilizer, which was calculated based on energy consumption of transport and the average transportation distance by train and truck. The $\text{GHG}_{\text{i}}$ is 0.09 kg CO₂ eq ha⁻¹ [15].

N rate is the nitrogen fertilization amount (kg N ha⁻¹). $\text{GHG}_{\text{others}}$ are the greenhouse gas emissions for phosphorus and potassium fertilizers production and transportation, which for phosphorus fertilizer production was 0.73 kg CO₂ eq ha⁻¹, and for transportation was 0.06 kg CO₂ eq ha⁻¹, and for potassium fertilizer production was 0.5 kg CO₂ eq ha⁻¹, and for potassium fertilizer transportation was 0.05 kg CO₂ eq ha⁻¹. The GHG emission per unit area, expressed as kg CO₂ eq ha⁻¹ and the GHG emission intensity, was expressed as kg CO₂ eq Mg⁻¹ grain.

The N₂O emission that come from nitrogen fertilizer applications to fields occur by direct and indirect pathways. The indirect pathway includes the NH₃ volatilization and NO₃⁻ leaching; the direct pathway is the N₂O emission from the soil. The calculation equations of direct N₂O emission and indirect N₂O emission for wheat [16-17] are as below:

Direct N₂O emission: $y=0.54 \exp (0.0063 \times N \text{ surplus})$

Note: The N surplus was the N fertilizer application rate minus the wheat total nitrogen uptake.

Indirect N₂O emission was estimated as 1% of NH₃ volatilization and 0.75% of NO₃⁻ leaching.

$$\text{NH₃ volatilization} = 13.59 \exp (0.009 \times \text{N rate})$$

$$\text{NO₃⁻ leaching} = 4.95 + 0.17 \times \text{N rate}$$

The total N₂O emission was calculated in units of CO₂ equivalents (CO₂ eq), and expressed as kg CO₂ eq ha⁻¹. The significance of GHG emissions between NE and FP at the 0.05 level of probability was compared based on least significant difference (LSD). And the correlations between PFPN with GHG emissions were simulated by using the Proc GLM and Proc NLIN procedures in SAS 9.2 software, respectively.

3. Results

3.1. Fertilizer application rates
Of all sites and years average (Table 2), the fertilizer surveys for farmer’s practices in this research showed that the fertilizer N application for FP was ranged from 245.6 to 301.6 kg ha⁻¹, the averaged N fertilization rate was 276.2 kg ha⁻¹. This data is similar to the reported farmers’ fertilizer survey of 250-300 kg N ha⁻¹ for winter wheat in this region [2, 17-18]. The NE fertilizer recommendation ranged from 149.3 to 182.0 kg ha⁻¹, the averaged N fertilization rate was 161.5 kg ha⁻¹, significantly lower than the FP.

Fertilizer P application in the FP ranged from 34.9 to 52.8 kg ha⁻¹, the averaged P fertilizer application rate was 45.0 kg ha⁻¹. The NE treatment P fertilization rate ranged from 58.2 to 68.2 kg ha⁻¹, the averaged P application rate was 62.0 kg ha⁻¹. The K fertilizer input for FP was from 25.5 to 59.2 kg ha⁻¹, and the average application rate was 43.9 kg ha⁻¹. The NE recommended K input was from 66.3 to 71.2 kg ha⁻¹, the average K application rate was 67.8 kg ha⁻¹. The NE system significantly reduced the nitrogen application rate while increased the phosphate and potassium fertilizer application rates to meet the wheat production need.

Table 2. Comparison of fertilization rates in wheat for NE and FP (kg ha⁻¹).

| Sites and Years | N application rate¹ | P₂O₅ application rate | K₂O application rate |
|----------------|---------------------|------------------------|----------------------|
|                | NE                  | FP                     | NE                   | FP       |
| XJ-2011        | 149.3b              | 301.6a                 | 58.2a                | 34.9b    |
| XJ-2012        | 153.1b              | 281.3a                 | 59.5a                | 52.8a    |
| ZD-2012        | 182.0b              | 245.6a                 | 68.2a                | 47.2b    |
| All sites & years | 161.5b             | 276.2a                 | 62.0a                | 45.0b    |

¹ For each sites and years, the fertilizer application rates are the average of all field trials.

3.2. Grain yield and nutrient use efficiency of PFPN
The yields for NE treatment in XJ and ZD were 3.7%-5.2% higher than for FP treatments, but there were no significantly grain yield differences in all sites and years (Table 3). But to PFPN, the NE treatment significantly higher than FP due to the lower fertilizer input, especially the lower N fertilizer input. The partial factor productivity of N for NE treatment was from 37.2 kg kg⁻¹ to 47.5 kg kg⁻¹ in XJ and ZD in two crop years. The averaged PFPN was 43.2 kg kg⁻¹, nearly double than for the FP treatments. The PFPN for NE in this research was very close to the China national average of 43.0 kg kg⁻¹ but higher than the North China Plain average of 33.9 kg kg⁻¹ [19]. These results showed the NE strategies can be used in the wheat nutrient recommendation to keep grain yield in the Hebei plain.

Table 3. Wheat grain yield and PFPN under different nutrient management.

| Year       | Locations | Sites | Grain Yield (kg ha⁻¹) | PFPN (kg kg⁻¹) |
|------------|-----------|-------|----------------------|----------------|
|            |           |       | CK                   | NE  | FP  |
| 2010-2011  | XJ        | 31    | 5965b                | 7638a| 7363a|
| 2011-2012  | XJ        | 12    | 5641b                | 7115a| 6846a|
| 2011-2012  | ZD        | 8     | 5385b                | 6765a| 6430a|
| All sites & years |       |       | 5664b                | 7173a| 6880a|

3.3. Estimated GHG emission
The N$_2$O emission had already been recognized as the main component of GHG balance and increased exponentially with nitrogen fertilizer input rate [16-17, 20]. In this research, the estimated winter wheat N$_2$O emission for FP was 1.85 kg N ha$^{-1}$, similar to reported 1.3-1.7 kg N ha$^{-1}$ [21], which was tested by continuous air flow enclosure method. The NE significantly reduced the N$_2$O emission to 0.69 kg N ha$^{-1}$ by reducing the N input than FP (Table 4). The excessive N fertilizer application in the FP treatment caused excessive emissions of direct and indirect N$_2$O of 0.68 and 0.47 kg N ha$^{-1}$, respectively.

The GHG emission due to N fertilizer input in this research was 95.0% and 98.2% for NE and FP, respectively. The GHG emissions for NE were 1686 kg CO$_2$ eq ha$^{-1}$ (Table 4), significant lower than the FP treatments of 3329 kg CO$_2$ eq ha$^{-1}$. The NE treatment significantly reduced 49.4% total GHG emissions and 50.4% GHG emission intensity than FP. The high N fertilizer use for FP treatment resulted in significantly higher GHG emission and GHG emission intensity than NE. This result suggested reducing N fertilization rate is very important in reducing GHG emission.

### Table 4 GHG emissions by fertilizer input for different nutrient management strategies.

| Treatments | N$_2$O emission (kg N ha$^{-1}$) | GHG emission (kg CO$_2$ eq ha$^{-1}$) | GHG emission intensity |
|------------|---------------------------------|--------------------------------------|------------------------|
|            | Direct | Indirect | Total | N fertilizer use | N fertilizer production | Others | Total | (kg CO$_2$ eq Mg$^{-1}$) |
| XJ2011     | NE     | 0.32b    | 0.25b | 0.58b | 270b | 1238b | 82a | 1590b | 267b |
|            | FP     | 0.80a    | 0.65a | 1.45a | 681a | 2500a | 53b | 3234a | 537a |
| XJ2012     | NE     | 0.64b    | 0.34b | 0.98b | 461b | 1269b | 86a | 1816b | 257b |
|            | FP     | 1.98a    | 1.11a | 3.08a | 1444a | 2332a | 73a | 3849a | 579a |
| ZD2012     | NE     | 0.34b    | 0.31b | 0.66b | 307b | 1509b | 90a | 1906b | 288b |
|            | FP     | 0.63a    | 0.50a | 1.13a | 527a | 2036a | 70a | 2633a | 418a |
| All sites & years | NE       | 0.41b | 0.28b | 0.69b | 325b | 1277b | 84a | 1686b | 252b |
|            | FP     | 1.09a    | 0.75a | 1.85a | 865a | 2403a | 61a | 3329a | 508a |

### 3.4 Correlation of GHG emission with PFPN

Significantly linear plus plateau correlations were found between GHG emission and nitrogen use efficiency of PFPN across all sites and years (Figure 1). The GHG emission decreased while the PFPN increasing, but when the PFPN higher than 41.3 kg kg$^{-1}$, the GHG emission had the trend of keeping at about 1538 kg CO$_2$ eq ha$^{-1}$. The GHG emission for NE more closely to the plateau area, and had the possibility of keeping lower GHG emission than FP. And on the other hand, the result suggested the NE treatment had the potential of decreasing the GHG emission through increasing the nutrient use efficiency. The further reducing GHG emission could be contributed to improving crop yield through enhancing the nutrient management technology level [22].
4. Results
Results from our study have demonstrated that Nutrient Expert system showed greater yields in NE with lower N input through improved fertilizer use efficiency while maintaining low total N<sub>2</sub>O emissions and GHG emissions. There were significantly linear plus plateau correlations between GHG emissions with nutrient use efficiency of PFP-N, which suggested the keeping the PFPN higher than 41.3 kg/kg is the pathway to reducing the GHG emissions in the Hebei Plain wheat production. This research in the 51 farmers’ field showed the potential of the Nutrient Expert for winter wheat could be easily used in smallholder farmers’ fertilizer recommendation, and could significantly decreased the N fertilizer input than farmers’ practice.

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