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# Optimal nitrogen input for higher efficiency and lower environmental impacts of winter wheat production in China

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ABSTRACT

Many fertilization guidelines have been established to recommend the proper nitrogen (N) application rate to optimize grain yield. However, environmental impacts and grain nutritional quality such as protein content have not received enough attention. To optimize regional N fertilizer management in China, a total of 1212 and 1110 sets of data from a literature survey and field experiments were used in a regression analysis to determine the relationships of N application rate with winter wheat grain yield and protein content, respectively. Regional N rate recommendations were estimated with the linear-plus-plateau model and were between the N rates used to maximize grain yield and protein content. The recommended N rates for the winter wheat–summer maize rotation (WM), winter wheat–rice rotation (WR), and rainfed winter wheat (RW) regions in China were 208–230 kg $ha^{-1}$, 150–195 kg $ha^{-1}$, and 117–134 kg $ha^{-1}$, respectively. These values were comparable to or lower than the investigated farm average in each region; however, calculated based on the linear-plus-plateau model, the recommended N rate in each region achieved 1–19% greater grain yield and 2–9% greater protein content compared with the farm average yield and protein content. Compared with the excessive N input group, the recommended N rates increased the N partial factor productivity ($PFP_N$) of wheat by 7–11, 8–14, and 18–24 kg $kg^{-1}$ and gained an additional profit of 214–228, 91–354, and 465–476 USD $ha^{-1}$ in the three regions, respectively; in addition, the recommended N rates reduced the residual inorganic N, nitrate leaching, and direct nitrous oxide emissions by 8–27%, 29–52%, and 19–36% in the three regions, respectively. These findings suggest that this N recommendation method provides an option to balance the yield, grain quality, income, nitrogen use efficiency, and environmental impacts of winter wheat production in China and similar cropping systems around the world.



## 1. Introduction

Wheat is a globally important food crop whose production accounts for more than 20% of the world's arable land. In China, the wheat cropping area is ~22% of the total sown area of grain crops (NBS, 2014). From 1978 to 2014, the annual wheat grain production in China increased by 126%, from 54 to 122 million tons, and the average grain yield per unit area increased by 174%, from 1.85 to 5.06 t $ha^{-1}$ (NBS, 2014). In the coming decades, higher yields will be necessary to feed the growing and increasingly wealthy population on the country's limited and decreasing cropland (Zhang et al., 2013a). Grain protein content is a critical trait of wheat. In developed countries, dietary protein can be obtained from various sources such as meat, legume seeds, and cereals, whereas in less developed countries, dietary protein intake depends largely on the amount of protein in cereals (Shewry, 2007), and this is the situation in China.

Nitrogen (N) is typically considered the most influential factor for wheat productivity and grain quality (Triboi et al., 2000; Zhang et al., 2013b), and N fertilizer is widely used to increase yield and economic profit in China (Zhu and Chen, 2002). Guided by the conventional concept of "the more fertilizer, the higher yield",

*Abbreviations:* WM, winter wheat–summer maize rotation region; WR, winter wheat–rice rotation region; RW, rainfed winter wheat region.

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China has seen a continuous increase in the amount of chemical N fertilization since the 1990s, and in most cases, N input is far greater than crop demand (Ju et al., 2009). In the North China Plain, the N application rate has reached as high as 325 kg N $ha^{-1}$, but this high input produces a relatively low wheat grain yield of 5.76 t $ha^{-1}$ (Ju et al., 2009). The great amount of N fertilization has increased yield slightly, but it has also caused serious environmental problems (Liu and Diamond, 2008). In a winter wheat–summer maize rotation system, a remarkable amount of residual inorganic N of 361 kg $ha^{-1}$ was observed in top 90 cm of soil at winter wheat harvest after continuously applying 300 kg N $ha^{-1}$ during successive wheat seasons (Ju et al., 2002).

The following problems are critical under the current rapid worldwide agricultural development: (1) ensuring sufficient yield to meet the increasing demand caused by growing population, (2) supplying enough protein for improved human health, (3) increasing economic returns to improve living standards and enthusiasm for crop production, and (4) reducing the negative impacts of fertilizer on the environment. Many studies have examined the relationship between wheat grain yield and N application rate at specific locations or different scales (Cerrato and Blackmer, 1990; Valkama et al., 2013; Gaudin et al., 2015) using several models including the quadratic, linear-plus-plateau, quadratic-plus-plateau, square root, and exponential models, and particularly in China, the quadratic model has been most commonly used (Chen et al., 2000; Zhang et al., 2008b; Hartmann et al., 2015). However, grain nutritional quality such as protein content and the environmental impacts caused by N fertilizer application have not received enough attention in most fertilizer recommendations.

Apart from N rate, other factors such as the type and timing of N supply (Fowler et al., 1990; Woolfolk et al., 2002; Wang et al., 2015), organic manure incorporation (Lin et al., 2015), and seasonal variation (Asseng and Milroy, 2006; Perilli et al., 2010; Gao et al., 2012) also influence wheat yield or protein content. However, N supply, which typically exceeds crop requirement, has become a major concern worldwide (Ju et al., 2009). Therefore, in the present paper, we mainly focused on optimizing N application rate. Using wheat N application in China as a typical case, we established national-scale datasets of N application rate, grain yield, and protein content by compiling data from experimental plots, and the objectives were (1) to predict an optimum N input level for high wheat grain yield, high grain protein content, and low environmental impacts and (2) to develop a method to optimize regional N fertilizer management by balancing yield, grain quality, income, N use efficiency and environmental impacts for similar cropping systems around the world.

## 2. Materials and methods

### 2.1. Study area

Winter wheat in China covers an area ~22.3 million ha, including three cropping systems distributed in different regions: (i) the winter wheat–summer maize rotation (WM) region (32°–41°N, 106°–121°E); (ii) the winter wheat–rice rotation (WR) region (24°–34°N, 9°–121°E); and (iii) the rainfed winter wheat (RW) region in northern China (34°–37°N, 104°–113°E) (Fig. 1). The sunshine hours, air temperature, precipitation, and sowing and harvest dates for wheat in these production regions are presented in Table 1.

### 2.2. Data collection

Regression relationships between N rate and grain yield and between N rate and grain protein content were established for making N recommendations for each region using data compiled from: (i) a “literature survey”, that is, literature published during 1990–2015 in China found in the China Knowledge Resource Integrated Database with search terms including “wheat”,

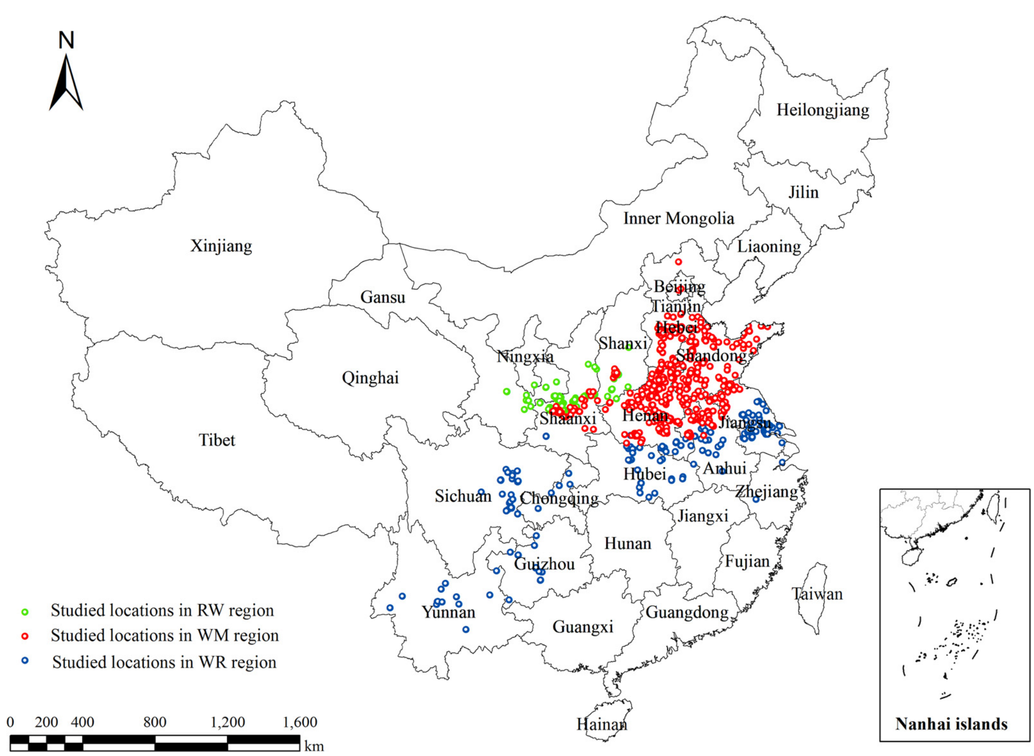


**Fig. 1.** Geographical distribution of studied locations in RW (rainfed winter wheat region in northern China), WM (winter wheat–summer maize rotation region), and WR (winter wheat–rice rotation region).

**Table 1**
Sunshine hours, air temperature, precipitation, and sowing and harvest dates for wheat in different production regions of China. WM, winter wheat–summer maize rotation region; WR, winter wheat–rice rotation region; RW, rainfed winter wheat region in northern China.

| Wheat regions | Sunshine hours ($ha^{-1}$) | Air temperature (°C) | | Precipitation (mm) | | Sowing date | Harvest date |
|---|---|---|---|---|---|---|---|
| | | Annual | Growing season | Annual | Growing season | | |
| WM | 1738–2440 | 6.4–14.6 | 7.6–10.7 | 570–1000 | 130–400 | Late September to early November | Late May to late June |
| WR | 832–2248 | 12.5–15.6 | 10.1–13.7 | 800–1250 | 230–500 | Early October to mid-November | Mid-April to early June |
| RW | 1848–2658 | 7.0–12.9 | 6.8–10.8 | 400–600 | 150–250 | Mid-September to early October | Late May to early July |

"nitrogen", "yield", "protein", and "quality"; and (ii) "field experiments", which include unpublished data from field experiments conducted by our research team and cooperators in the RW region. To ensure a uniform representation, specific criteria were proposed for the data selection: (1) data were obtained through experiments carried out under field conditions; (2) data sets such as N rate-grain yield, N rate–grain protein content, or N rate–grain yield–grain protein content were included; (3) the datasets were not from particularly high-yielding cultivation conditions or high-fertility fields used for high- or super high-yielding purposes, i.e., with no N fertilization, wheat grain yields were >6 t $ha^{-1}$ in the WM region and > 5 t $ha^{-1}$ in the WR and RW regions, and protein contents of >14.0% in each region were excluded; and (4) the experimental site was stated. In total, 1212 (1048 from the literature survey and 164 from field experiments) and 1110 (909 from the literature survey and 201 from field experiments) datasets were respectively used in regression analyses of grain yield and protein content versus N rate for N recommendations.

In addition, "farm investigations" were also conducted in 2009, 2010, 2011, 2013, and 2014 to evaluate N application, wheat grain yield, and protein content in farms (Liu et al., 2014). Nitrogen rates used by farmers and the corresponding wheat grain yields were obtained through a questionnaire survey, and grain protein contents were determined by our research team.

For data from the literature survey, around 8% of research sites applied manure, and the average soluble N input of these sites was 113 kg $ha^{-1}$; for data from field experiments, as we focused on chemical fertilizers, no soluble N was added; and for data from farm investigations, 7% of farmers applied manure, equivalent to an average soluble N input of 89 kg N $ha^{-1}$. Since the proportion of manure was very small in data sets, manure soluble N was not included in N fertilizer input in the present paper. The data sources used in this paper are presented in Table 2. These data were from a wide range of soil types and fertility statuses, climatic conditions, cultivation strategies, fertilizer management practices, and wheat varieties, and thus substantially represented the local and regional N fertilization practices, grain yields, and protein contents.

*2.3. Data analysis*

To compute the N rate–yield and N rate–protein content relationships for making N recommendations, data with large variations in grain yield and protein content were compiled, and these datasets were considered to be a reasonable reflection of the large variations in environmental conditions and management measures throughout the study area. To guarantee a wide representation, outlying data that exceeded three times the standard deviation were eliminated (Table 2).

All data collected from farm investigations were used in evaluating N application, wheat grain yield, and protein content in farms, which were shown in box-whisker plots generated using GraphPad Prism 5.01. To compute the N rate–yield and N rate–protein content relationships using data from the farm investigations, outlying data that exceeded three times of the standard deviation were eliminated, and only 5 sets of N rate-yield data in WM regions were finally eliminated. The regression equations for the two relationships were established using the quadratic and linear-plus-plateau models as described by Cerrato and Blackmer (1990), with SPSS 13.0 and PROC NLIN of the SAS System for Windows V8, respectively.

The N partial factor productivity ($PFP_N$, kg $kg^{-1}$) was used to describe the N fertilizer productivity, which is defined as the grain yield produced by per unit of fertilizer N (Cassman et al., 1998) and calculated as:

$$PFP_N = Y/F_N,$$

where Y (t $ha^{-1}$) is the wheat grain yield and $F_N$ (kg of N $ha^{-1}$) is the corresponding N fertilizer application rate.

In each region, an optimum N rate was recommended and a corresponding wheat grain yield and then $PFP_N$ were calculated. Using the $PFP_N$ value, a corresponding N fertilizer rate was calculated for the grain yield in each farm. A higher farm N rate compared with the calculated rate indicates that "excessive N" was used, and the opposite indicates "insufficient N". Of the farmers using "insufficient N", if their wheat yield was higher or lower than that gained at the recommended N rate in the corresponding region, then this means the farmer used "insufficient N with higher yield" or "insufficient N with lower yield".

The relative economic return was calculated as: (wheat price × wheat yield increment) − (N fertilizer price × increment in amount of N fertilizer). The average prices of wheat and N fertilizer were 0.340 and 0.623 USD $kg^{-1}$ (1 US dollar = ~6.2 Chinese Yuan Renminbi) over the past two decades, computed from China's food information network (http://www.grain.gov.cn/

**Table 2**
Data used for regression analyses of grain yield and protein content versus N rate, and for evaluation of farm N application, wheat grain yield, and protein content.

| | Regression analyses | | | | Farm evaluation | | |
|---|---|---|---|---|---|---|---|
| | N-yield | | N-protein content | | N rate | Yield | Protein content |
| | Literature | Experiments | Literature | Experiments | Farm | Farm | Farm |
| WM | 668 (3) | 0 | 579 (4) | 0 | 467 | 467 | 467 |
| WR | 294 (1) | 0 | 247 | 0 | 185 | 185 | 185 |
| RW | 86 | 164 | 83 | 201 (1) | 101 | 101 | 101 |

WM, winter wheat-summer maize rotation region. WR, winter wheat-rice rotation region. RW, rainfed winter wheat region in northern China. Data provided in parentheses refer to the number of eliminated observation.

Grain/Wheat.aspx) and China's fertilizer network (http://www.fert.cn/), respectively.

*3.1. Environmental impacts related to N fertilization*

The environmental impacts related to N fertilization were evaluated for different wheat production regions, including residual inorganic N, nitrate leaching, and direct nitrous oxide emissions, however, nitrate leaching and direct nitrous oxide emissions in RW were excluded due to limited data. The relationships between environmental impacts and N rates were established from data collected though a literature survey, using equations that have already been elucidated in previous studies, or from our field experiments carried out to study residual inorganic N responding to N application in the WM region during 2005–2013 (Table 3). The literature survey was conducted using the Web of Science and the China Knowledge Resource Integrated Database to identify articles published before January 2015 to investigate the relationship between residual inorganic N and N rate. Articles were screened according to the following criteria: (1) the studies were conducted under field conditions in at least one of the WM, WR, or RW regions; (2) both residual inorganic N and N rate were reported; and (3) residual inorganic N was measured at wheat harvest after an entire winter wheat growing season, i.e., from sowing to harvest. In addition, if crop rotation was employed, only the wheat–rice or wheat–maize rotation was included.

## 4. Results and discussion

*4.1. Responses of wheat grain yield and protein content to N application rate*

*4.1.1. Responses of wheat grain yield to N application rate*

Based on data from the literature survey and field experiments, the relationships between N rate and grain yield and between N rate and grain protein content were determined. A large database covering a wide range of N application rates (0–394, 0–375, and 0–320 kg ha$^{-1}$) and yield variations (2.37–9.92, 1.56–9.03, and 1.27–7.60 t ha$^{-1}$) was used to determine the N rate–grain yield relationship in the WM, WR, and RW regions, respectively (Fig. 2). With no N fertilization, the average yield was 4.31, 3.55, and 3.18 t ha$^{-1}$, and N fertilization increased the yield to an average of 7.04, 6.09, and 5.81 t ha$^{-1}$ in the three regions, respectively. In each region, both the quadratic and linear-plus-plateau models described the N rate–grain yield relationship with similar $R^2$ values. $R^2$ values for the three regions indicated that 35–53% of yield gain was due to increased use of N fertilizer. Bell et al. (1995) conducted a case study on wheat in northwest Mexico from 1968 to 1990 and found that 48% of the total yield gain was attributed to increased use of N fertilizer and 28% to genetic gain, leaving 24% unexplained. Based on the quadratic model, maximum grain yields of 7.46, 6.52, and 6.26 t ha$^{-1}$ were obtained with 284, 266, and 291 kg N ha$^{-1}$ in the WM, WR, and RW regions, and according to the linear-plus-plateau model, maximum yields of 7.42, 6.48, and 5.87 t ha$^{-1}$ were achieved at 208, 195, and 117 kg N ha$^{-1}$, respectively.

The quadratic model has been commonly used to describe the response of crops to N fertilization (Chen et al., 2000; Zhang et al., 2008b; Hartmann et al., 2015). However, previous studies (Cerrato and Blackmer, 1990; Chen et al., 2000) and the present study indicate that this model tends to produce an excessively high optimum fertilization rate, which may explain the high N application rates in China. For example, in the WM and WR regions, the two models produced similar maximum yields, but the corresponding N rates in the quadratic model were 76 and 71 kg ha$^{-1}$ higher than those calculated with the linear-plus-plateau model, a 37% and 36% difference, respectively. Since 2001, when an article describing the linear-plus-plateau model was published in Chinese (Chen et al., 2000), more and more attention has been focused on decreasing N rates based on this model. However, this model has rarely been used for N recommendations of actual production.

*4.1.2. Responses of protein content of wheat grain to N application rate*

In the WM, WR, and RW regions, nitrogen application rates of 0–375, 0–338, and 0–320 kg ha$^{-1}$ and protein content variations of 7.6–17.5%, 8.0–16.8%, and 6.9–16.0% were used to determine the N rate–protein content relationship, respectively, with protein content of wheat receiving no N application being 11.3%, 9.8%, and 10.9%, and nitrogen fertilization increased protein content to an average of 13.8%, 12.0%, and 12.9%, respectively. Due to long-term differences in climate, weather, soil, hydrology, etc. from north to south, the protein accumulation rate of northern wheat due to N fertilizer is more enhanced than that of southern wheat, whereas the difference between eastern and western wheat is much smaller (Qi et al., 2012).

**Table 3**
Equations used to estimate the residual inorganic N in the top 100 cm of soil at wheat harvest, and nitrate leaching and nitrous oxide emission rates as affected by N fertilization (x, kg ha$^{-1}$). WM, winter wheat-summer maize rotation region. WR, winter wheat-rice rotation region. RW, rainfed winter wheat region in northern China. ** and *** indicate significance at the 0.01 and 0.001 levels, respectively.

| Environmental impact | Winter wheat region | Equation |
|---|---|---|
| | WM | $^{a}y = 60.9e^{0.0042x}$, $R^2 = 0.45^{***}$ |
| Residual inorganic N (kg N ha$^{-1}$) | WR | $^{b}y = 62.2e^{0.0020x}$, $R^2 = 0.24^{***}$ |
| | RW | $^{c}y = 59.6e^{0.0037x}$, $R^2 = 0.58^{***}$ |
| Nitrate leaching (kg N ha$^{-1}$) | WM, WR | $^{d}y = 2.7e^{0.0088x}$, $R^2 = 0.25^{**}$ |
| Direct nitrous oxide emission (kg N ha$^{-1}$) | WM, WR | $^{e}y = 0.33e^{0.0054x}$, $R^2 = 0.43^{**}$ |

[a] Equation was established using data from our own research and through a literature survey (Cui et al., 2006; Cui et al., 2010; Dong et al., 2012; Guo et al., 2008; Jiang et al., 2010; Ju et al., 2002; Ju et al., 2003; Liu et al., 2003; Liu et al., 2002; Ning et al., 2010; Qiu et al., 2012; Shi and Yu, 2006; Sun et al., 2011; Wang et al., 2007; Wang et al., 2006; Wei et al., 2010; Xu et al., 2010; Ye et al., 2010; Zhang et al., 2010; Zhao, 2004; Zhao et al., 2006; Zhong et al., 2006) including 194 sets of observations. In the present study, residual inorganic N was calculated within the top 100 cm of the soil profile after wheat harvest.

[b] Equation was established through a literature survey (Fan et al., 2004; Fan et al., 2007; Lin et al., 2010; Shi et al., 2012; Shi et al., 2010; Yang et al., 2013; Yi et al., 2010) including 44 sets of observations.

[c] Equation was established through a literature survey (Gao et al., 2005; Gao et al., 2009; Li et al., 2011a; Li et al., 2013; Li et al., 2011b; Liang et al., 2012; Zhang et al., 2009) including 44 sets of observations.

[d,e] Equations were elucidated in a previous study (Cui et al., 2014). In this study, equation was established by compiling literature that reported nitrate leaching and direct nitrous oxide emissions throughout the entire growing season caused by N fertilization under field conditions in wheat–maize and wheat–rice systems. Nitrate leaching means the amount of nitrate that leached down to 90, 100, or 120 cm. Direct nitrous oxide emission refers to nitrous oxide loss through a direct pathway, i.e., directly from the soil to which nitrogen fertilizer was added.

References for Table 3 could be found in supplementary information.

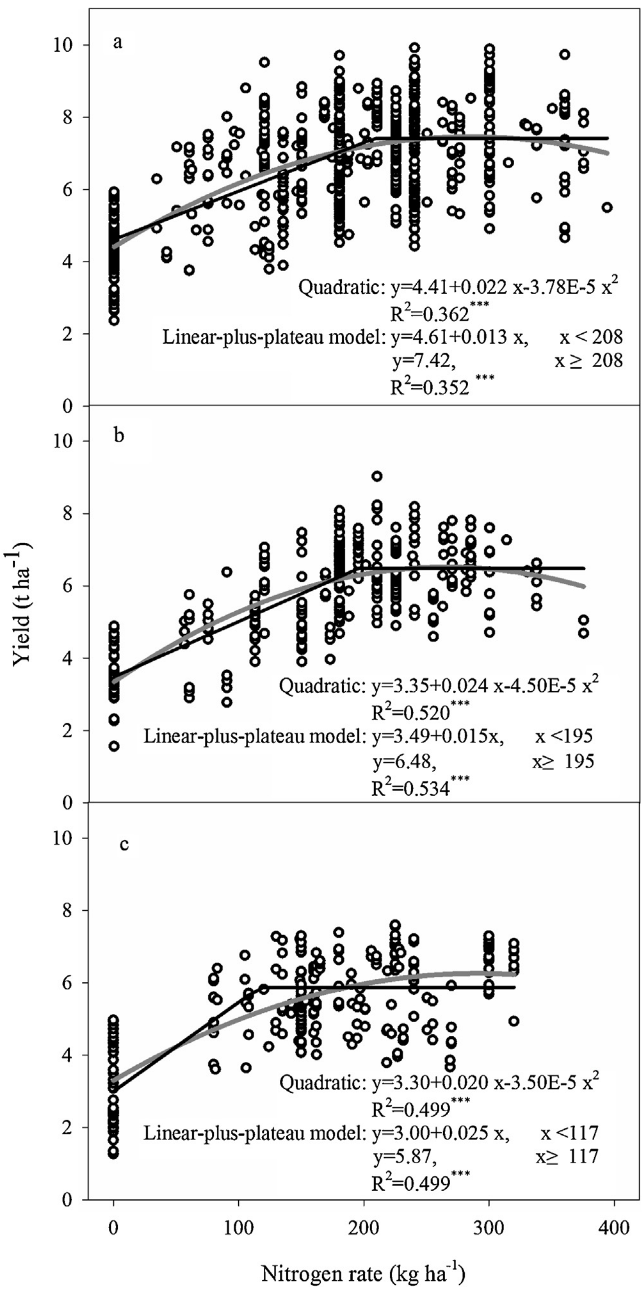


**Fig. 2.** Grain yield as a function of N rate in different wheat production regions. Data are from a literature survey and field experiments. (a) Winter wheat–summer maize rotation region. (b) Winter wheat–rice rotation region. (c) Rainfed winter wheat region in northern China. ***Indicates significance at the 0.001 level.

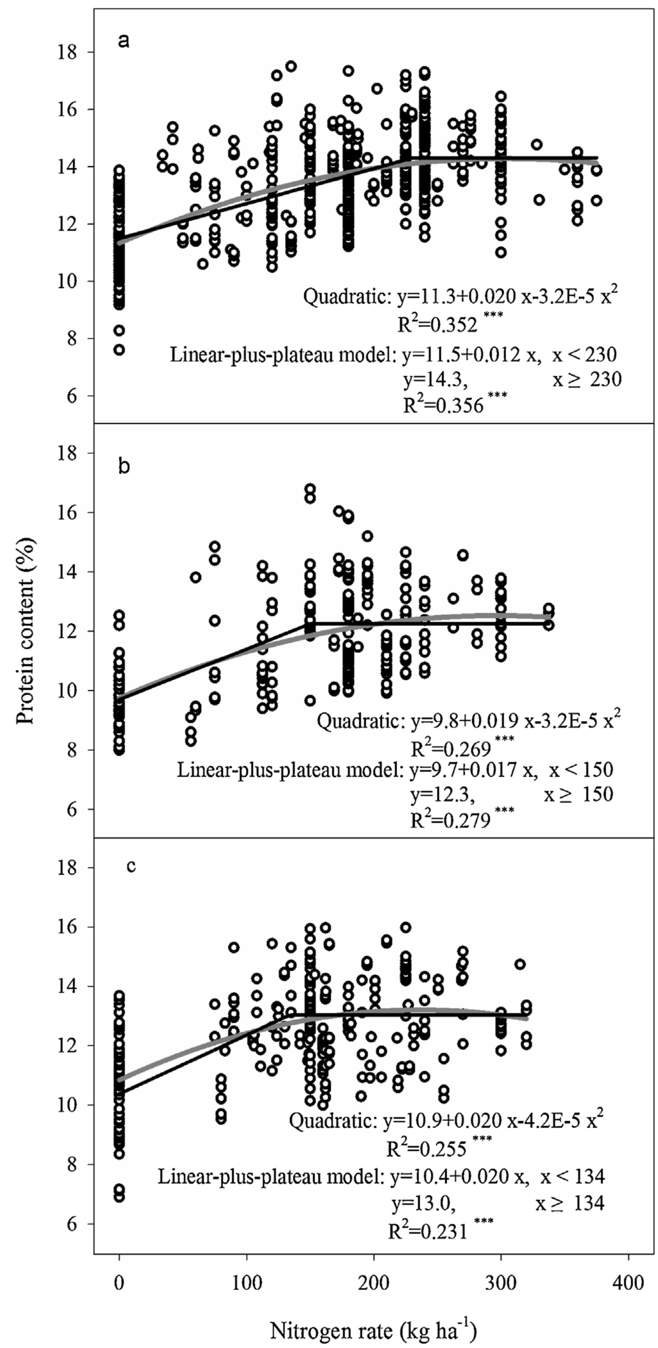


**Fig. 3.** Grain protein content of wheat as a function of N rate in different wheat production regions. Data are from a literature survey and field experiments. (a) Winter wheat–summer maize rotation region. (b) Winter wheat–rice rotation region. (c) Rainfed winter wheat region in northern China. *** indicates significance at the 0.001 level.

The quadratic and linear-plus-plateau models described the N rate–grain protein content relationship with similar $R^2$ values in each region (Fig. 3). Based on the quadratic model, the maximum grain protein content in the WM region was 14.3% and obtained with a rate of 304 kg N ha$^{-1}$; according to the linear-plus-plateau model, the same maximum value was obtained with a far smaller N rate of 230 kg ha$^{-1}$. In the WR region, a maximum grain protein content of 12.5% and 12.3% was obtained at N rates of 296 and 150 kg ha$^{-1}$, respectively. In the RW region, maximum protein contents of 13.2% and 13.0% were reached at N rates of 237 and 134 kg ha$^{-1}$, respectively. Again, there were marked discrepancies between the N rates needed to achieve the maximum grain protein content. The N rates calculated with the quadratic model were 74, 146, and 103 kg ha$^{-1}$ higher than those calculated by the linear-plus-plateau model in the WM, WR, and RW regions, representing a 32%, 97%, and 77% difference, respectively. However, the maximum grain protein contents were nearly the same for each region. Previous studies have shown that when excess N is applied, grain protein content reaches a maximum and then remains stable (Cui et al., 2005; Yue et al., 2012). Furthermore, genetic potential restricts increases in grain protein content despite ample N supply (Barneix, 2007).

*4.2. Nitrogen fertilizer recommendations based on balancing grain yield and protein content*

The main goal of agricultural production has traditionally been increasing cereal grain yield to feed an increasing population and meet improving living standards. However, a recent study suggested that 37% of global wheat areas are now experiencing yield stagnation, and in China, the wheat yield in 56% of agricultural areas has been stagnating (Ray et al., 2012). Equally importantly, the focus for wheat has been achieving high-protein content, first for improved nutritional quality and second for enhanced processing performance (Shewry, 2007), and selective breeding for high grain protein content has been a primary objective for breeders (Barneix, 2007). The N rate–grain yield and N rate–grain protein content relationships presented in this study may be valuable tools to predict the N rates needed to achieve target grain yield and protein content. Using these relationships, we selected the appropriate model to make N recommendations for each region.

Selecting a suitable model for a particular cropping system is of great importance for estimating optimal N rates, and the model should consider the goodness of fit of the data as well as the amount of fertilizer estimated by the model. Specifically, based on the linear-plus-plateau model, a lower N rate of 208 kg ha$^{-1}$ results in a sufficiently high wheat grain yield of 7.42 t ha$^{-1}$ in the WM region. At this point, the grain protein content is 14.0%, as the effect of N fertilizer on the grain protein content has not been fully realized. Based on the linear-plus-plateau model, the grain protein content reaches a maximum value at an N rate of 230 kg ha$^{-1}$ and can be as high as 14.3%. Therefore, to maintain adequate grain yield and protein content with less N, an N rate of 208–230 kg ha$^{-1}$ is recommended in the WM region. Based on the linear-plus-plateau model, the highest grain protein content of 12.3% was obtained at an N rate of 150 kg ha$^{-1}$ in the WR region, however, the grain yield at this rate is only 5.79 t ha$^{-1}$. Based on the linear-plus-plateau model, an N rate of 195 kg ha$^{-1}$ can achieve a sufficiently high yield of 6.48 t ha$^{-1}$. Therefore, an N rate of 150–195 kg ha$^{-1}$ is recommended in the WR region. Based on the quadratic model, an N rate of 291 kg ha$^{-1}$ ensures the highest wheat grain yield of 6.26 t ha$^{-1}$ in the RW region. However, based on the linear-plus-plateau model, if the N rate is reduced to 117 kg ha$^{-1}$, although the grain yield will decrease by 6%, the N rate will decrease by 60%. In the RW region, water is the major factor limiting crop growth and water deficit restricts the effect of N on yield potential, which is more obvious in dry years. Thus, the higher N rate of 291 kg ha$^{-1}$ will not fully benefit the yield in this region, and the lower N rate of 117 kg ha$^{-1}$ is more practical. At this point, the grain protein content is 12.7%, and based on the linear-plus-plateau model, the grain protein content reaches a maximum at an N rate of 134 kg ha$^{-1}$ and can be as high as 13.0%. Therefore, an N rate of 117 to 134 kg ha$^{-1}$ is recommended in the RW region.

Based on the analyses above, the recommended N rates in the present study for different regions of China estimated by the linear-plus-plateau model are set between the rates necessary to maximize grain yield and protein content (Fig. 4).

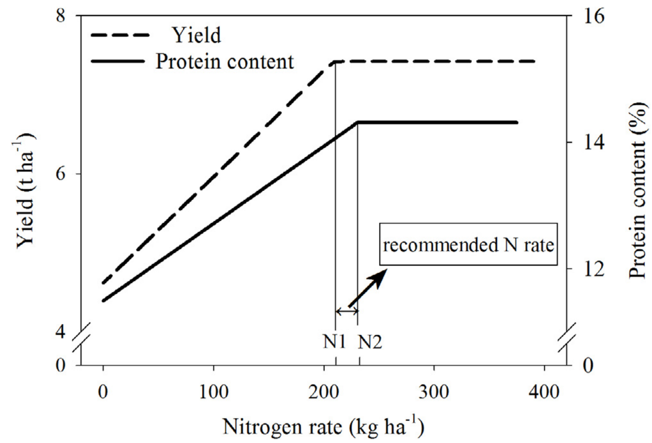


**Fig. 4.** Recommended N rate estimated between the rate to maximize grain yield (N1) and protein content (N2) by the linear-plus-plateau model using the winter wheat–summer maize rotation region as an example.

*4.3. Grain yield and quality benefits of recommended N inputs compared with farm practices*

*4.3.1. Nitrogen rate, wheat grain yield, and protein content of farm practices*

Our 5-year farm investigations show that N fertilization is a very important practice of local farmers. Almost all the investigated farmers applied N fertilizer in wheat growing seasons, although some applied very little, e.g., < 30 kg ha$^{-1}$. Nevertheless, a number of farmers applied very high amounts of N. For example, 10% of the farmers in the WM region applied N at a rate > 320 kg ha$^{-1}$, and some used rates as high as 750 kg ha$^{-1}$. In China, winter wheat–summer maize rotation is a very important agricultural practice, and it is used in ~70% of the national wheat production. Farmers in the WM region usually apply N in very large amounts to guarantee high wheat yield per unit area. For example, farmers applied N with a mean rate of 325 kg ha$^{-1}$ in the North China Plain, a typical wheat–maize rotation system (Ju et al., 2009).

The average application rates in the three regions were in the following order: WM (224 kg ha$^{-1}$) > RW (175 kg ha$^{-1}$) > WR (164 kg ha$^{-1}$), with standard deviations of 83, 60, and 88 kg ha$^{-1}$, respectively. In the WM, RW, and WR regions, 50% of farmers applied N fertilizer at rates of 173–270, 137–202, and 113–220 kg ha$^{-1}$, and 90% used rates of 102–345, 105–275, and 0–316 kg ha$^{-1}$, respectively (Fig. 5a). The average N rate estimated for the three regions is 202 kg N ha$^{-1}$, which is in accordance with that of 210 kg N ha$^{-1}$ obtained from farm investigations (Chen et al., 2014). This indicates that the data used in this study are reliable and representative.

The grain yields from the WM, WR, and RW regions averaged 7.31, 5.58, and 4.94 t ha$^{-1}$ with standard deviations of 1.43, 1.35, and 1.67 t ha$^{-1}$, respectively. For each region, 50% of the wheat yields ranged from 6.66 to 8.25, 4.50 to 6.69, and 3.53 to 6.30 t ha$^{-1}$, and 90% ranged from 4.50 to 9.29, 3.35 to 7.52, and 2.38 to 7.50 t ha$^{-1}$, respectively (Fig. 5b). Across all three regions, the wheat yield averaged 6.57 t ha$^{-1}$, more than double the global average of 3.03 t ha$^{-1}$, but still lower than some countries such as Germany (8.00 t ha$^{-1}$) and France (7.25 t ha$^{-1}$) (FAO, 2014).

Similar to the N rates, the grain protein contents were highest in WM (13.1%), followed by RW (12.4%) and WR (11.8%), with standard deviations of 1.3%, 1.5%, and 1.7%, respectively, and 70%, 48% and 32% of the values were higher than the level of 12.5% needed for bread making, respectively (Turner et al., 2004). For each region, 50% of the grain protein contents ranged from 12.3% to 13.9%, 11.4% to 13.2%, and 10.7% to 13.0%, and 90% ranged from 10.8% to 15.1%, 10.5% to 15.1%, and 9.1% to 14.5%, respectively (Fig. 5c). Across all three regions, the average protein content was 12.7%, which is still low compared with that of wheat cultivated in Siberia from 1900 to 2008 ( > 16.0%) (Morgounov et al., 2013), Finland (protein content of 95% of grain exceeds 13.0%) (Peltonen-Sainio et al., 2012), and 372 bread wheat types from 70 different countries (average 14.5%) (Bordes et al., 2008). We have no available data to identify the cause of these differences in protein contents, but we can assume that the yield may have contributed, as the yields in Siberia and Finland were as low as 1.88–4.21 t ha$^{-1}$ and 3.28–4.72 t ha$^{-1}$, which

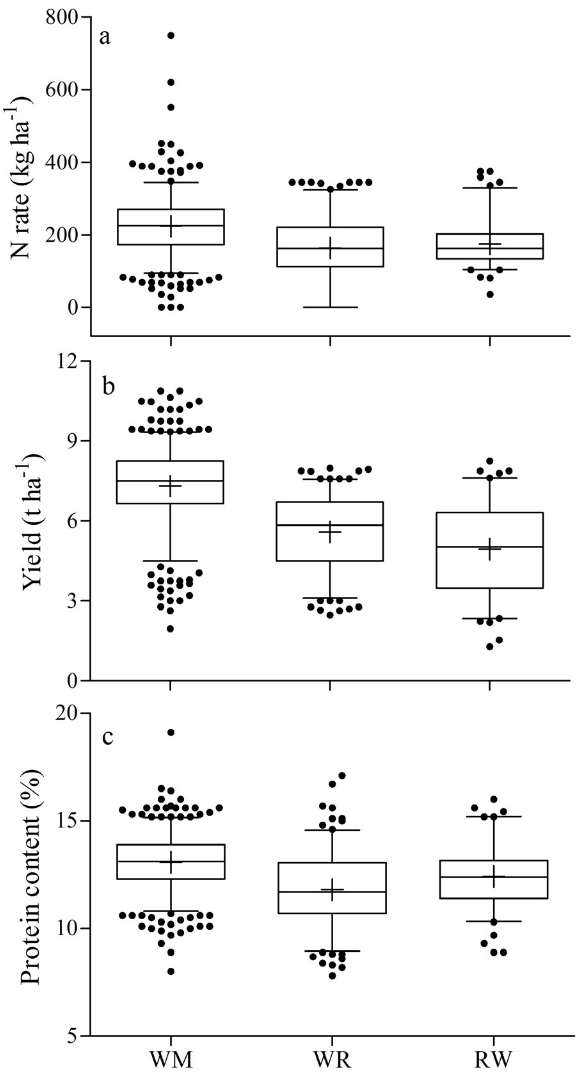


**Fig. 5.** Nitrogen application rate (a), wheat grain yield (b), and grain protein content (c) in local farms in different wheat production regions. WM, winter wheat-summer maize rotation region. WR, winter wheat-rice rotation region. RW, rainfed winter wheat region in northern China. The line and plus sign within the box represent the median and mean of all data, respectively; the lower and upper box edges, whisker caps, and dots represent 25 and 75, 5 and 95, and <5 and >95 percentiles of all data, respectively.

reflect the well-known negative relationship between wheat grain yield and protein content (Oury and Godin, 2007). Environmental factors and genotype may also influence protein content, with a stronger effect from environmental factors (Triboi et al., 2000; Shewry, 2007).

*4.3.2. Grain yield and quality benefits of the recommended N inputs*

In the WM, WR, and RW regions, the recommended N rates achieved grain yields of approximately 7.42, 5.79–6.48, and 5.87 t $ha^{-1}$, indicating that the grain yield produced by 1 kg N fertilizer (i.e., $PFP_N$) was 32.3–35.7, 33.2–38.6, and 43.8–50.2 kg $kg^{-1}$, respectively. Using these $PFP_N$ values, a corresponding N fertilizer rate was calculated for the grain yield in each farm. A higher farm N rate compared with the calculated rate indicates that "excessive N" was used, and the opposite indicates "insufficient N". It was observed that 43%, 43%, and 84% of the farmers applied excessive N, and 41%, 43% and 9% applied insufficient N in the three regions, respectively. Of the farmers using "insufficient N", 24%, 22%, and 7% of the farmer used "insufficient N with higher yield", and 18%, 22%, and 2% of the farmers used "insufficient N with lower yield" in the WM, WR, and RW regions, respectively.

Compared with the average wheat yield and protein content of the excessive N input group, calculated based on the linear-plus-plateau model, the recommended N rate in each region can achieve 4–28% greater yield and 2–8% greater protein content (Table 4), revealing that over-fertilization does not further increase yield but wastes resources. Compared with the insufficient N with lower yield group, the recommended N rates could achieve 16–55% greater yield and 6–29% greater protein content, indicating that insufficient N input limits potential for wheat yield and protein content (Zhang et al., 2008a). The insufficient N with higher yield group achieved greater yield compared with that at the recommended N rate, however, these low N rates may restrict increased yield sustainability because crop growth may deplete the soil nutrient pool (Brown et al., 1999). Furthermore, recommended N rates gained 3–11% higher protein content in three regions.

Overall, averaged farm practices of 224, 164, and 175 kg N $ha^{-1}$ achieved an average yield of 7.31, 5.58, and 4.94 t $ha^{-1}$ and an average protein content of 13.1%, 11.8%, and 12.4% in the WM, WR and RW regions, respectively. It is noteworthy that although the recommended N rates in the WM and WR regions were comparable with and those in the RW region were far lower than the corresponding investigated farm average, calculated based on the linear-plus-plateau model, the recommended N rate in each region can still achieve 1–19% higher grain yield and 2–9% higher protein content compared with the farm average yield and protein content. The yield benefits gained from the recommended N rates in WM and WR can also be found with regression curves of the farm observations. The two models can also describe these regressions, and again the linear-plus-plateau model performed better (Figs. 6 and 7). Using regression curves of farm observations, farmers achieved a maximum yield of 7.66 t $ha^{-1}$ with an N rate of 246 kg $ha^{-1}$ in the WM region. Although the recommended N rate resulted in 3% lower yield, the amount of N used was reduced by 15%. Moreover, the $R^2$ value was only 0.06 for the farm observations. In the WR region, using the yield response curve from the farm observations, farmers achieved a maximum yield of 6.24 t $ha^{-1}$ with an N rate of 196 kg $ha^{-1}$, however, the recommended N rate of 195 kg $ha^{-1}$ could achieve higher grain yield of 6.48 t $ha^{-1}$. However, N application had no significant effect on grain yield in the RW region or on grain protein content in all regions using farm data.

The main reason for the lower grain yield and quality in the investigated farms was that farmers applied inappropriate N, that is, too much or too little. In China, farmers usually decide how much N to apply according to experience rather than soil testing, especially in rural areas where the cropping index is high. Moreover, the short time interval between the first crop harvest and the second crop planting makes soil testing unfeasible, and farmers usually have less access to soil testing facilities (Zhu and Chen, 2002). Furthermore, the data used in the recommendations were from field experiments (Table 2), and researchers usually manage their fields better by applying fertilizer to deeper soil depths and at appropriate growing periods according to plant demands, as well as by controlling pests and weeds, etc. Therefore, the field experiments usually achieved higher grain yields with lower N rates. This also indicates that with better management, the fertilizer N rate can be reduced considerably without a loss in grain yield (Zhu and Chen, 2002). The above analyses indicates that farmers should use proper N rates and better manage crop growth conditions to ensure the steady increases in crop yield and quality.

**Table 4**
Grain yield, protein content, partial factor productivity ($PFP_N$), relative economic return, and environmental impacts related to N at the recommended N input compared with farm excessive and insufficient N input. WM, winter wheat–summer maize rotation region; WR, winter wheat–rice rotation region; RW, rainfed winter wheat region in northern China.

| Wheat region | | Average N rate ($kg\,ha^{-1}$) | Yield ($t\,ha^{-1}$) | Protein content (%) | $PFP_N$ ($kg\,kg^{-1}$) | Relative economic return ($USD\,ha^{-1}$) | Residual inorganic N ($kg\,ha^{-1}$) | Nitrate leaching ($kg\,ha^{-1}$) | Nitrous oxide emission ($kg\,ha^{-1}$) |
|---|---|---|---|---|---|---|---|---|---|
| WM | Rec. N | 208–230 | 7.42 | 14.0–14.3 | 32–36 | – | 146–160 | 17–20 | 1.0–1.1 |
| | Exc. N | 282 | 6.89 | 13.2 | 25 | −214 to −228 | 199 | 32 | 1.5 |
| | Ins. N | 161 | 7.61 | 12.9 | 52 | 96–109 | 120 | 11 | 0.8 |
| | Ins. N with lower yield | 128 | 6.40 | 12.9 | 54 | −284 to −298 | 104 | 8 | 0.7 |
| | Ins. N with higher yield | 185 | 8.51 | 12.9 | 51 | 386–400 | 132 | 14 | 0.9 |
| WR | Rec. N | 150–195 | 5.79–6.48 | 12.3 | 33–39 | – | 84–92 | 10–15 | 0.7–0.9 |
| | Exc. N | 234 | 5.59 | 12.1 | 25 | −91 to −354 | 99 | 21 | 1.2 |
| | Ins. N | 92 | 5.41 | 11.5 | 58 | −65 to −327 | 75 | 6 | 0.5 |
| | Ins. N with lower yield | 54 | 4.19 | 11.6 | 61 | −455 to −718 | 69 | 4 | 0.4 |
| | Ins. N with higher yield | 130 | 6.63 | 11.5 | 55 | 63–326 | 81 | 8 | 0.7 |
| RW | Rec. N | 117–134 | 5.87 | 12.7–13.0 | 44–50 | – | 92–98 | nc | nc |
| | Exc. N | 184 | 4.59 | 12.4 | 26 | −465 to −476 | 118 | nc | nc |
| | Ins. N | 110 | 6.66 | 11.9 | 67 | 273–284 | 90 | nc | nc |
| | Ins. N with lower yield | 70 | 4.88 | 10.1 | 88 | −298 to −309 | 77 | nc | nc |
| | Ins. N with higher yield | 121 | 7.17 | 12.4 | 61 | 440–450 | 93 | nc | nc |

Rec. N, recommended N rate; Exc. N, excessive N rate; Ins. N, insufficient N rate; nc, not calculated, due to limited data.

### 4.4. Nitrogen use efficiency of recommended N inputs

On a national or regional scale, $PFP_N$ is the only index of N use efficiency that can be estimated reasonably well, as its calculation does not require data of grain and/or plant N uptake or grain yield in unfertilized plots (Dobermann, 2005). In addition, farmers are mostly concerned with the total economic output and the return from input investments. Therefore, $PFP_N$ was used as an index of N use efficiency in this paper. Compared with the excessive N input group, the $PFP_N$ of wheat at the recommended N rate increased by 7–11, 8–14, and 18–24 $kg\,kg^{-1}$ in the WM, WR, and RW regions, respectively (Table 4), indicating that excessive N fertilization results in resource waste as well as a reduction in wheat productivity per unit of N used.

The $PFP_N$ of wheat at the recommended N rate of 208–230 $kg\,ha^{-1}$ in the WM region ranged from 32 to 36 $kg\,kg^{-1}$, which is comparable with the $PFP_N$ of 33 $kg\,kg^{-1}$ at a similar N rate of 226 $kg\,ha^{-1}$ in a maize–soybean–wheat rotation in north-east Italy (Basso et al., 2007) and higher than that of 27 $kg\,kg^{-1}$ at a similar N rate of 225 $kg\,ha^{-1}$ under the same crop system in Mexico (Limon-Ortega et al., 2000). In the WR region, the $PFP_N$ at the recommended N rate of 150–195 $kg\,ha^{-1}$ was in the range of 33–39 $kg\,kg^{-1}$, which is higher than that of 27 $kg\,kg^{-1}$ at 180 N $kg\,ha^{-1}$ under the same crop system in India (Yaduvanshi, 2003). However, the $PFP_N$ of wheat at the recommended N rates in the WM or WR regions are lower than the average for wheat in France (48 $kg\,kg^{-1}$) (Laratte et al., 2014) and cereal crops worldwide (44 $kg\,kg^{-1}$) (Dobermann, 2005), whereas the $PFP_N$ in the RW region (44–50 $kg\,kg^{-1}$) is comparable to the France or the world average.

### 4.5. Economic return of recommended N inputs

Achieving the maximum profit from wheat production is the most fundamental goal for farmers. The recommended N rates result in increased economic returns compared with the excessive N input group, specifically, 214–228, 91–354, and 465–476 USD $ha^{-1}$ for the WM, WR, and RW regions, respectively (Table 4). In parts of the WM region, a fertilizer recommendation method based on yield response to N (or phosphorus or potassium) and agronomic efficiency can increase economic benefits by 107 USD $ha^{-1}$ compared with reported farm practices (Chuan et al., 2013). This increase is higher than the 33–47 USD $ha^{-1}$ increase resulting from the recommended N rates compared with the investigated farm average in the present study in the WM region.

### 4.6. Environmental impacts of recommended N inputs

The recommended N rates resulted in higher grain yield, protein content, N use efficiency, and economic return, and reduced environmental stress. Specifically, compared with excessive N inputs, the recommended N rates can reduce residual inorganic N by 20–27%, 8–15%, and 17–22%, that is 39–54, 7–15, and 20–26 $kg\,ha^{-1}$ in the WM, WR, and RW regions, respectively (Table 4). Furthermore, these recommended rates can reduce nitrate leaching by 37–48% and 29–52%, that is 12–16 and 6–11 $kg\,ha^{-1}$, and reduce direct nitrous oxide emissions by 25–33% and 19–36%, that is 0.4–0.5 and 0.2–0.4 $kg\,ha^{-1}$ in the WM and WR regions, respectively. Recent studies also showed that comparable or increased yields could be realized with lower N inputs, and therefore lower environmental costs (Liu et al., 2011; Chen et al., 2014; Yang et al., 2015).

Appropriate amounts of N fertilizer should be applied for wheat production, as insufficient N input results in poor grain quality and may restrict yield potential and sustainability. However, when excessive N is applied, grain yield or quality may not further increase; instead the $PFP_N$ and economic return may decline and potential environmental hazards can occur. At present, the average cereal yield and $PFP_N$ in Western Europe and North America are above the global average due to the combination of favorable climate, fertile soil, appropriate N fertilizer management practices, etc. (Dobermann, 2005). Although climate and soil conditions are difficult to control, improvements in N management through this N recommendation method can be achieved to increase grain yield

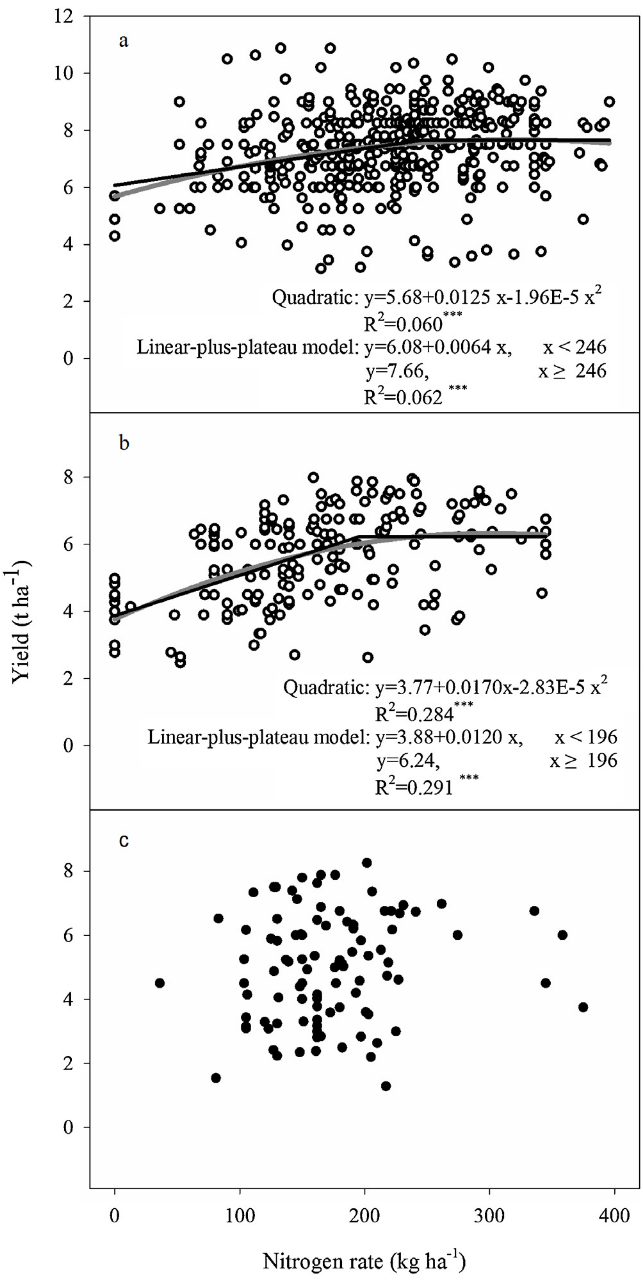


**Fig. 6.** Grain yield as a function of N rate in WM (a), WR (b), and RW (c) regions. Data are from farm investigations. WM, winter wheat–summer maize rotation region. WR, winter wheat–rice rotation region. RW, rainfed winter wheat region in northern China. ***Indicates significance at the 0.001 level.

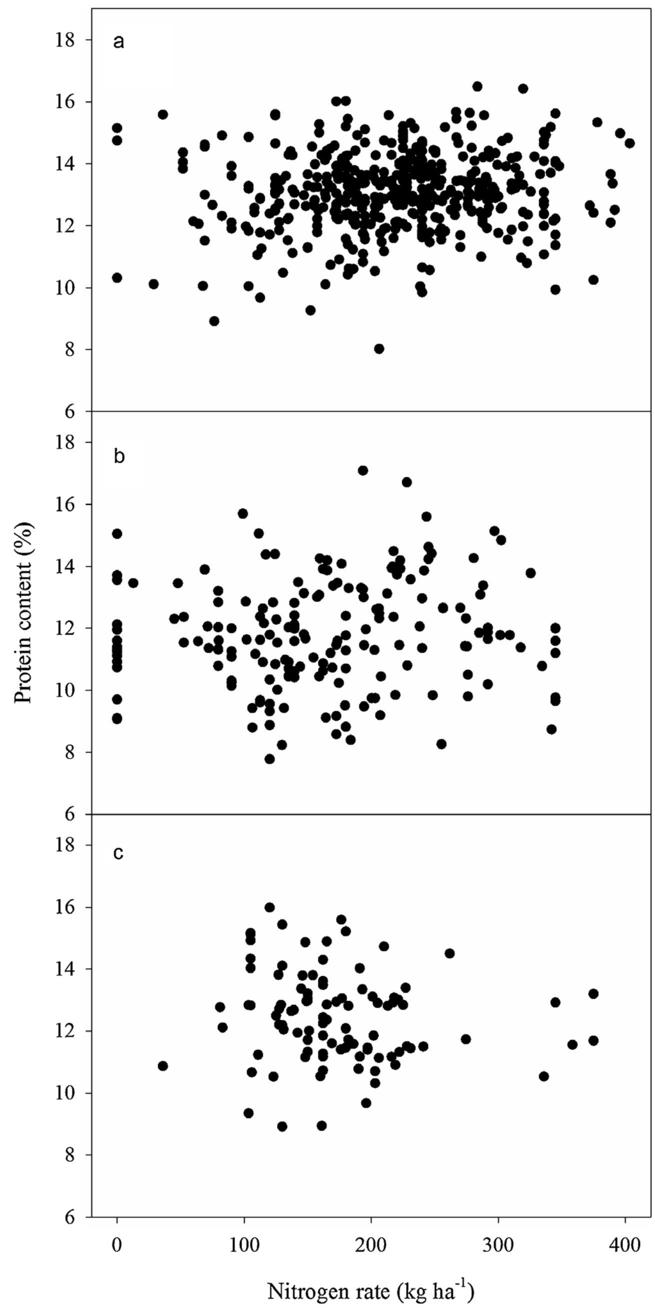


**Fig. 7.** Grain protein content of wheat as a function of N rate in WM (a), WR (b), and RW (c) regions. Data are from farm investigations. WM, winter wheat-summer maize rotation region. WR, winter wheat–rice rotation region. RW, rainfed winter wheat region in northern China. ***Indicates significance at the 0.001 level.

and $PFP_N$ in China. It should be recognized that this N recommendation method was developed as a general recommendation over a large regional scale and achieves higher yield with lower and appropriate N input in each study region. Site-specific N requirements should be regulated and determined in accordance with local conditions, since previous studies have found that the type, timing, and blend of N fertilizers, type and fertility of soil, and seasonal variability may also cause differences in yield. For example, nitrate N has better effect than ammonium N on wheat yield in most rainfed farming systems (Wang et al., 2015). Late-season foliar N applications just before or immediately following flowering (Woolfolk et al., 2002), as well as increasing the use of polymer-coated urea (Farmaha and Sims, 2013), may significantly increase grain protein content. The grain yield and protein content are higher in plants grown in clay-loam soil than those grown in sandy-loam soil (Masoni et al., 2007). Grain yield and protein content are also influenced by soil fertility (Metho et al., 1999; Hlisnikovsky et al., 2015) and seasonal variability, mainly associated with rainfall and temperature (Asseng and Milroy, 2006; Gao et al., 2012).

It has been well documented that China has been facing larger environmental challenges than many other major countries (Liu and Diamond, 2005), and a great extent of these issues comes from the overuse of N fertilizer in agricultural production (Liu et al., 2013). Reducing N rates from “excessive” to “moderate” can help control the acceleration of environmental degradation. Many published studies have perhaps overemphasized the situation of excessive N application, but insufficient N fertilization is also a very serious and urgent problem in China. Therefore, to correct the current situation of excessive N fertilization, we should stress not only reducing N fertilization in some areas, but also increasing the N rates in areas with poor soil fertility or insufficient N fertilization.

## 5. Conclusions

Nitrogen rate recommendations between the rates necessary to maximize grain yield and protein content were estimated with the linear-plus-plateau model. For the WM, WR, and RW regions, N rates of 208–230 kg ha$^{-1}$, 150–195 kg ha$^{-1}$, and 117–134 kg ha$^{-1}$ are recommended, respectively. These values are comparable to or lower than the investigated farm average in each region, however, the recommended N rates can still increase grain yield by 1–19% and protein content by 2–9% compared with the farm average in the three regions. Compared with the excessive N input group, the recommended N rates can increase the $PFP_N$ of wheat by 7–24 kg kg$^{-1}$, gain additional profits of 91–476 USD ha$^{-1}$, and reduce residual inorganic N, nitrate leaching, and direct nitrous oxide emissions by 8–27%, 29–52%, and 19–36%, respectively. This analysis suggests that our N recommendation method can balance the yield, grain quality, income, N use efficiency, and environmental impacts of winter wheat production and serve as a valuable guideline for wheat production, especially in rural areas of China and similar cropping systems around the world.

In the present paper, we focused on optimizing N rates for wheat production, as inappropriate N application is an urgent issue in China. However, there is still a need for future research to include other factors such as soil productivity, variety, precipitation, tillage system, etc. that can also affect wheat yield or quality, and therefore N recommendation.

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## Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.agee.2016.03.022.

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