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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",

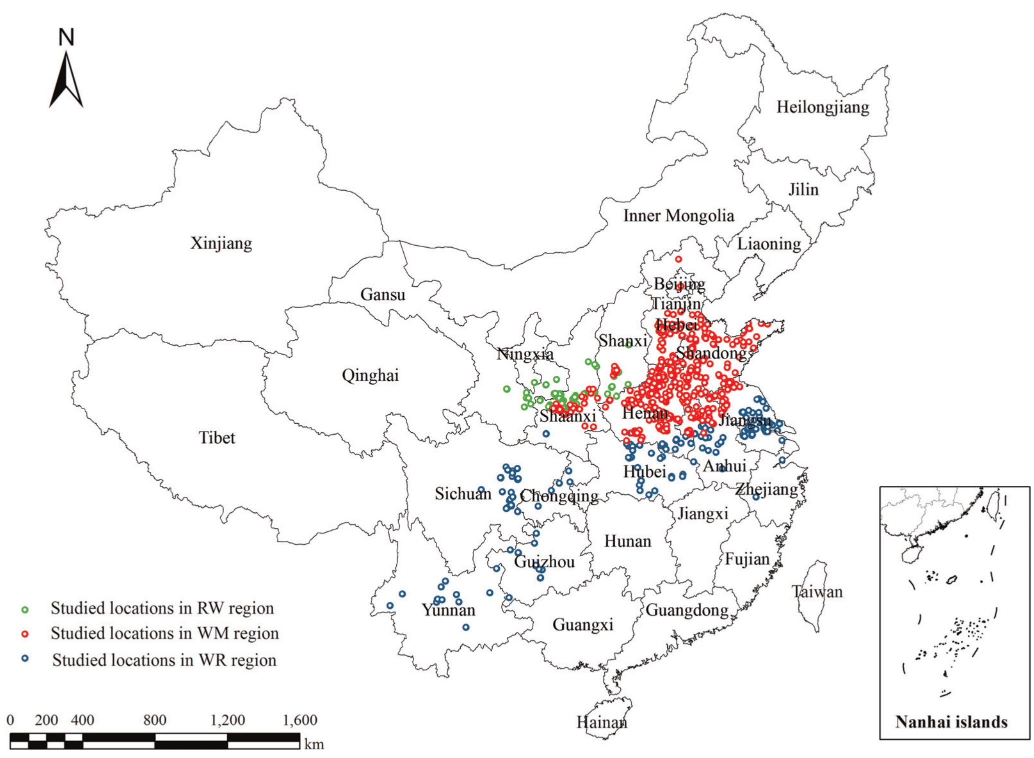

Fig. 1. Geographical distribution of studied locations in RW (rainfed winter wheat region in northern China), WM (winter wheat–summer maize rotation region), and WR (winter wheat–rice rotation region).