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Spatial variation of attainable yield and fertilizer requirements for maize at the regional scale in China

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ABSTRACT

Understanding attainable yield, soil nutrient supply capacity and fertilizer requirements in current intensive maize (*Zea mays* L.) production at regional and national scales in China is essential in making informed decisions on policy, research and investment. In this study, results of a large number of on-farm experiments (n = 5893) were collected for the period 2001–2015 from the main maize production areas in China to study the spatial variability of attainable yield, relative yield (RY) and fertilizer requirements by coupling geographical information system with the Nutrient Expert for Hybrid Maize system. We found strong spatial variation in attainable yield across all sites, with a coefficient of variation (CV) of 25.5%. Mapping the spatial variability of RY indicated that 85.3%, 79.3% and 72.5% of RY for nitrogen (N), phosphorus (P) and potassium (K) of the study areas ranged from 0.68 to 0.87, from 0.83 to 0.95 and from 0.84 to 0.94, respectively. The RY was higher in North Central China than other regions. The RY can reveal the spatial heterogeneity of soil nutrient supply capacity, and has been integrated into crop management strategies for calculating fertilizer requirements using the Nutrient Expert for Hybrid Maize decision support system. Overall, there were large variations in N, P and K fertilizer requirements across all sites with CVs of 19.5%, 31.6% and 35.0%, respectively, and the ranges of 150–210 kg N ha^{-1}, 50–90 kg P_2O_5 ha^{-1} and 50–110 kg K_2O ha^{-1} accounted for 72.0%, 81.7% and 81.5% of the study areas, respectively. The results of 605 field experiments in 10 provinces during 2010–2014 showed that the Nutrient Expert for Hybrid Maize system not only reduced N and P fertilizer application rates by 31.6% and 15.5%, respectively, but also increased maize yield by 3.3% compared with farmers' current practices. The combination of the fertilizer recommendation system and geographical information system with a large database of field trials provides a useful tool to identify spatial variation in fertilizer requirements in fields and regions, and contributes towards more efficient and effective fertilizer management.

1. Introduction

Crop yields have substantially increased over the past two decades, driven by the increasing use of chemical fertilizer, improved crop varieties and agronomic management (Mueller et al., 2012; Chen et al., 2014). However, the challenges for further potential yield increases are heightened by the increasing costs of inorganic fertilizer, soil degradation, decreasing arable land and increasing water and air pollution (Ju et al., 2009; Guo et al., 2010). Low nutrient use efficiency and environmental pollution are caused

Abbreviations: AY, attainable yield; K, potassium; MLYR, the Middle and Lower reaches of the Yangtze River; N, nitrogen; NC, north-central China; NE, northeast China; NW, northwest China; P, phosphorus; RY, relative yield; SW, southwest China.

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by over use of fertilizers or imbalanced fertilization, which has resulted in a major threat to food security, ecological safety and sustainable agricultural development (Zhang et al., 2013; Chen et al., 2014).

As one of the most effective approaches to addressing these problems, nutrient management plays an important role in improving fertilizer efficiency and increasing yield. Fertilizer application rates are largely dependent on soil nutrients; however, there is substantial variability in soil indigenous nutrient supply and crop responses to nutrients in different fields as a result of differences in crop-growing conditions, soil and crop management, and climate (Simmonds et al., 2013; He et al., 2015). Increased development of information-based soil and crop management technologies to manage this variability is required to further increase crop yield and nutrient use efficiency. To overcome the challenge, optimized nutrient management was developed on the basis of soil testing (He et al., 2009). However, there are some limitations to fertilizer recommendation based on soil testing—labor-intensive, time-consuming, and low correlations between indigenous nutrient supply and soil testing values (Dobermann et al., 2003).

Nutrient management strategies that use aboveground crop responses to quantify crop nutrient requirements can be effective, because fertilizer nutrients applied to soils will be eventually absorbed by plants and can be reflected by crop yield increase. Many yield response models have been used to estimate economic optimum nutrient rates, such as the fertilizer effect function equation (Greenwood et al., 2001; Sonar and Babhulkar, 2002), and the recommendation from relationship between yield response and soil nutrient supply (Bélanger et al., 2000; Cui et al., 2008a). Yield response is determined by the soil indigenous nutrient supply, and the two are negatively correlated (Xu et al., 2014a). Therefore, yield response can reflect the soil nutrient supply conditions and can be developed as a guideline for fertilizer recommendations (Xu et al., 2014a).

Maize (*Zea mays* L.) is the most widely planted crop in China and plays an important role in food security. However, Chinese intensive maize systems suffer from low productivity and low nutrient use efficiency. Excessive or imbalanced fertilization has led to nitrogen (N) recovery efficiency of less than 30% for most farmers (He et al., 2009; Xu et al., 2014b). The yields obtained by farmers are often below the attainable yield (AY) using the best local technology and modern crop management practices under field or station experiment conditions (Chen et al., 2011; Meng et al., 2013). This indicates that blanket fertilizer recommendations for large areas have serious limitations and that a new approach is required to provide integrated nutrient management. Geostatistical analysis has played an important role in soil and crop nutrient site-specific management (Robertson et al., 2008; Simmonds et al., 2013). Based on the best-fit semivariogram model and kriging interpolation method, maps for each variable can be obtained and have been used extensively to explain and characterize the spatial variability of soils and crop yields (Wang et al., 2009; Tsirulev, 2010).

Study of the maize nutrient requirements at a regional scale using agronomic effective and environmental friendly practice is crucial to avoid resources waste, ensure food safety and protect the ecological environment. Currently, blanket fertilization recommendations for large areas based on individual sites and limited data cannot meet the demands of intensive agricultural production. As a result, it is urgent to establish fertilizer recommendation at the regional scale based on a large number of experiments. Therefore, the objectives of this study were to: (1) analyze the current maize yield distribution; (2) map the distribution of relative yield (RY); (3) develop fertilizer recommendations at the regional scale; and (4) validate our recommendation with comparison to farmers' practices under numbers of field experiments at large scale.

2. Materials and methods

2.1. Study area

The study area was located in the main maize production regions in China, which was divided into five regions according to diverse geographic, climatic conditions and distribution of experimental sites (Fig. 1a): northeast (NE), northwest (NW), southwest (SW), north-central (NC) and the Middle and Lower reaches of the Yangtze River (MLYR). Spring and summer maize are both grown in China. Spring maize is mainly planted under a mono-cropping system in the NE and NW where cool temperatures are dominant. The NC region is dominated by a temperate climate and maize is usually cropped in a winter wheat–summer maize rotation. The SW and MLYR regions have a temperate, subtropical humid and sub-humid climate, and summer maize is either grown in rotation with winter wheat or with rape, rice or other crops.

2.2. Data sources

The data used in this study were obtained from the International Plant Nutrient Institute (IPNI) China Program, our research group and published articles in journals in the Web of Science database (www.cnki.net). Data from a total of 5893 on-farm experiments were collected for the period 2001–2015, which were conducted on a wide range of maize farms across China (Fig. 1b). The experimental sites covered almost all maize-growing regions and included different environments, soil types and cropping systems. The obtained data included the large numbers of maize varieties under the treatments of optimal nutrient management, farmers' practices and a series of nutrient omission treatments for N, phosphorus (P) and potassium (K).

2.3. Method of fertilizer recommendation

The Nutrient Expert for Hybrid Maize decision support system was used to make fertilizer recommendation for each experimental site. The Nutrient Expert system is a computer-based decision support system for nutrient management that was developed by IPNI. It is based on yield response and agronomic efficiency, and the system advocates site-specific nutrient management with the 4R nutrient stewardship: applying the right source of nutrients, at the right rate, right time and in the right place. This is combined with quantitative evaluation of the fertility of tropical soils model (Janssen et al., 1990) to simulate optimal nutrient uptake (Xu et al., 2013) and develop site-specific fertilizer recommendations (Xu et al., 2014a, 2014b). The yield response is used to evaluate the soil nutrient supply capacity or soil fertility (Xu et al., 2014a), while the percentile of RY is used to estimate yield response when yield response is not available. The RY is calculated from the yield response and AY (Pampolino et al., 2012). The internal parameters of the Nutrient Expert system were updated using the database information for 2001–2015.

The Nutrient Expert system scales maximum AY for a geographic region or growing environment according to site characteristics and farmers' actual yield. The AY in the system is determined from field trials or local experts' experience. To estimate AY, the Nutrient Expert system uses a decision rule and the level of risk in the growing environment—classified as low, medium or high based on the probabilities of drought or flood and any problem soils (e.g. salinity or degradation). In low-risk environments, estimated AY = maximum AY; however, for high-risk scenarios, estimated AY < maximum AY, with the minimum value for estimated AY equal to farmers' yield.

The yield response to fertilizer N, P and K is the yield gap between plots that receive ample nutrients and omission plots from

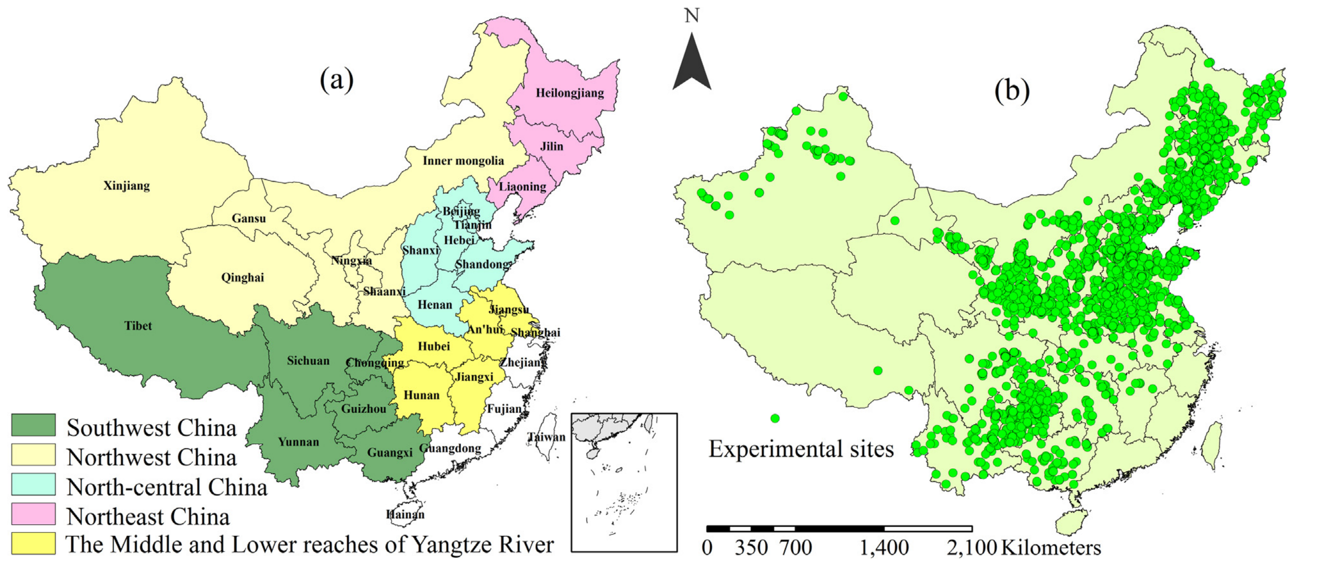

Fig. 1. Geographical distribution of the studied locations (a) and experimental sites (b) in the five study regions of China.

which one of the nutrients omitted. The percentile of RY representing soil fertility level can be used to estimate yield response which is calculated from the yield response and AY when yield response data are unavailable (Pampolino et al., 2012). The agronomic efficiency (AE) of fertilizer N, P and K (AE_N, AE_P and AE_K, respectively) represents the yield increase per unit of fertilizer N, P_2O_5 and K_2O applied, respectively. AE is related to yield response and fertilization rate. In the current study, AE was derived from a summary of multiple sites across different ecological zones, and determined at optimal amounts of added nutrients, not excessive or low fertilizer application rate.

The determination of fertilizer N requirements was mainly based on expected yield response to fertilizer and target agronomic efficiencies of applied N.

$$\text{Fertilizer N} = YR_N/AE_N$$

where fertilizer N rate is fertilizer N requirement (kg ha^{-1}), YR_N is yield response to fertilizer N application (kg ha^{-1}), AE_N is agronomic efficiency to fertilizer N application (kg kg^{-1}).

The determination of fertilizer P and K requirements considers the internal efficiency combined with estimates of AY, nutrient balance and yield responses to the added nutrient within a specific field. The P and K balances were used to estimate predict the residual P and K resulting from the previous crop. To maintain soil fertility, nutrients removed by the grain or harvested plant parts must be returned to the soil in the form of fertilizer. Most of the P (65%) taken up by the crop is accumulated in the grain, while most of the K (77%) remains in the straw (Xu et al., 2013). Therefore, Nutrient Expert system considered 70% of the P that is removed with the grain to be returned to the soil in the form of fertilizer. For K, 100% of the K removal with the grain and portion of K removed with the straw (depending on crop residue return) was accounted for in the K balance to prevent soil K mining. Nutrient Expert system gives dynamic/flexible fertilizer recommendations due to the different environmental conditions across different years and also the possible different management from previous residual nutrients (e.g. fertilizer rate applied and retained straw from previous crops).

$$\text{Fertilizer P} = (YR_P \times RIE_P/RE_P + AY \times RIE_P \times HI_P \times X_G\%) \times 2.292$$

where the unit of fertilizer P rate is fertilizer P_2O_5 requirement (kg ha^{-1}), YR_P is yield response to fertilizer P application (kg ha^{-1}), RIE_P is reciprocal internal efficiency, which is the nutrient uptake requirement per tonne of grain yield (kg t^{-1}), RE_P is recovery efficiency to fertilizer P application (%), AY is attainable yield (kg ha^{-1}), HI_P is P harvest index, $X_G\%$ is the return proportion of grain to guarantee the P balance and 2.292 is a conversion constant.

$$\text{Fertilizer K} = (YR_K \times RIE_K/RE_K + AY \times (RIE_K \times HI_K \times 100\% + RIE_K \times (1 - HI_K) \times X_S\%)) \times 1.205$$

where the unit of fertilizer K rate is fertilizer K_2O requirement (kg ha^{-1}), YR_K is yield response to fertilizer K application (kg ha^{-1}), RIE_K is nutrient uptake requirement per tonne of grain yield (kg t^{-1}), RE_K is recovery efficiency to fertilizer K application (%), AY is attainable yield (kg ha^{-1}), HI_K is K harvest index, $X_S\%$ is the return proportion of straw to guarantee the K balance and 1.205 is a conversion constant.

The Nutrient Expert system 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 such as water availability, flooding and drought problems, and soil-related problems (e.g. acidity and salinity) are embedded into the Nutrient Expert to estimate AY and yield response.

2.4. Analysis

The RY for N, P and K (RY_N, RY_P and RY_K) was defined as the yield ratio between nutrient-limited yield and AY, and was used as a coefficient to estimate yield response when yield response data were unavailable. In the current study, the RY_N, RY_P and RY_K values were calculated to represent soil N, P and K supply capacities, respectively. The AY in this study was defined as the maximum AY derived in field experiments, which was used to assess the yield distribution characteristics.

An optical remote-sensing image based on terrestrial ecosystems was used to identify the maize fields from the land cover classifications. We used GS+5.3 (Plainwell, Michigan, USA) and ArcGIS 9.3 software (ESRI, Redlands, USA) to map the distribution of RY and fertilizer requirements across the study plots using semivariogram models in conjunction with ordinary kriging. Semivariogram models were cross-validated and determined by the GS+ software, while ArcGIS 9.3 software was used to generate the spatial

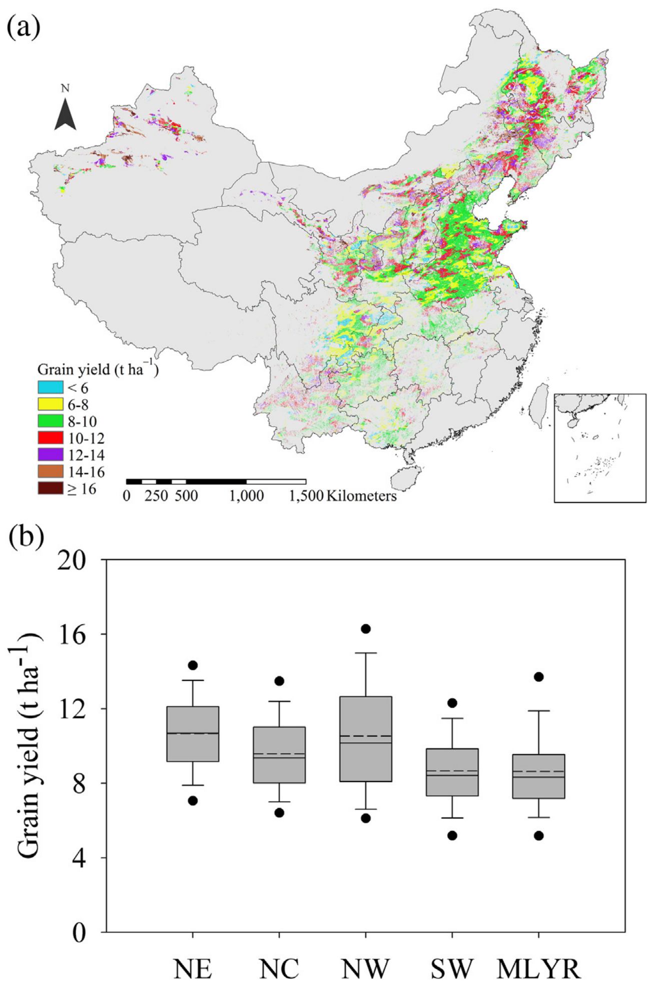

Fig. 2. Distribution of maize attainable yield (a) in China, and the box plots of grain yield for five regions in this study (b), solid and dashed lines indicate median and mean, respectively. The box boundaries indicate the upper and lower quartiles, the whisker caps indicate 90th and 10th percentiles, and the circles indicate the 95th and 5th percentiles.

distribution maps for each variable using ordinary kriging interpolation. Values for unmeasured locations were estimated from the weighted averages of values from nearby observed locations.

3. Results

3.1. Spatial distribution of maize yield

The AY showed a clear spatial distribution with an increasing trend from SW to NE and NE regions, which was mainly related to climate and rotation system: the conventional tillage of two crops a year in NC, SW and MLYR with summer maize and mono-cropping of the NE and NW regions with spring maize (Fig. 2a).

On average, the AY was 9.9 t ha^{-1} across all sites, with coefficient of variation (CV) of 25.5%. The AY values were 10.7, 9.6, 10.5, 8.7 and 8.6 t ha^{-1} for NE, NC, NW, SW and MLYR, respectively, with corresponding CVs of 21.0%, 22.6%, 30.3%, 25.7% and 28.6% (Fig. 2b). The AY in the range of 8–10 t ha^{-1} accounted for 37.9% of the study areas and was mainly distributed in the NC region and the north of MLYR and NE regions. The AY in the range of 10–12 t ha^{-1} accounted for 23.5% of the study areas and was mainly distributed in the black soil belt of NE and central NC, and in the southwest of the SW region. The AY in the NW region, such as northwest and middle Gansu and most of Xinjiang, was more than 12 t ha^{-1}, and exceeded 15 t ha^{-1} in some areas of Xinjiang. We found that 8.8% of the study areas had AY of 12–14 t ha^{-1}, and 5.7% of the areas exceeded 14 t ha^{-1} across all regions. However, AY was less than 8 t ha^{-1} in 24.1% of the areas, mainly in the south NC, north MLYR and in the Sichuan Basin (SW region).

3.2. Spatial distribution of RY

The RY was calculated based on yield response and AY, and used to represent soil nutrient supply capacity or soil fertility. Higher RY_N, RY_P or RY_K values indicate a high soil supply capacity for that nutrient. The CVs of RY_N, RY_P and RY_K were 17.0%, 12.2% and 12.0%, respectively. In the current study, the soil fertility level was classified by the 10th, 25th, median, 75th and 90th percentile of the RY. The CVs of RY_N were 8.3%, 8.6%, 12.5%, 12.8% and 8.9% for the NE, NC, NW, SW and MLYR regions, respectively (Fig. 3a). The majority of RY_N values were within 0.68–0.79, which accounted for 66.1% of the study areas. The RY_N range of 0.79–0.87 accounted for 19.2% of the areas, and was mainly located in the central NC. The RY_N range of 0.60–0.68 accounted for 11.7% of the areas, mainly located in the west NW region (Gansu, Qinghai and Ningxia). The low RY_N of less than 0.60 (2.3% of the areas) was mainly located in the east SW. However, RY_N exceeded 0.87 in about 0.7% of the study areas.

The RY_P values of 0.83–0.89 accounted for 44.8% of the study areas and were distributed across every region (Fig. 3b). The RY_P values of 0.89–0.95 (34.5% of areas) were mainly located in the NC and NE regions. High P fertilizer application from previous crops led to high RY_P and exceeded 0.95 in 3.1% of the study areas, mainly located in the central NC. The low RY_P values were mainly located in the NW and east SW regions and 15.0% of the study areas had RY_P values of 0.75–0.83, while RY_P was lower than 0.75 in only 2.6% of the study areas.

The RY_K values (Fig. 3c) of 0.84–0.90 accounted for 49.5% of the study areas, which were mainly located in the central NE, most of NC and in the SW region. The RY_K values of 0.90–0.94 accounted for 23.0% of the areas, and 5.3% of the areas had RY_K above 0.94, mainly located in the central NC. In most areas of the NW, the effect of applied K fertilizer exceeded 15%. Of all areas, about 22.2% showed an effect of applied K fertilizer of above 16% (RY_K < 0.84).

3.3. Spatial distribution of fertilizer requirements

The distribution of N fertilizer requirements indicated a large spatial heterogeneity for all regions, with 19.5% variation (Fig. 4a). Of the study areas, 42.9% had N fertilizer requirements within 150–180 kg N ha^{-1}, mainly distributed in the NE and NC, central SW and east NW regions. Fertilizer N of 180–210 kg N ha^{-1} accounted for 29.1% of the study areas. Furthermore, many areas of the NW region had N fertilizer requirements of more than 210 kg N ha^{-1}owing to high AY (Fig. 2a) and low RY_N (Fig. 3a). In 17.5% of the study areas, such as central NC, north NE and east Sichuan (SW region), 150 kg N ha^{-1}or less met the crop requirements. However, more N fertilizer was needed in high-yielding areas, such as central NC and Xinjiang in the NW region.

There was strong spatial variability in P fertilizer requirements among regions, with CV of 31.6% (Fig. 4b). The P fertilizer requirements were higher for spring than for summer maize planting regions. In 49.9% of the study areas, P fertilizer application rate was 50–70 kg P_2O_5 ha^{-1}, mainly in the NC, MLYR, north SW and north NE regions. Fertilizer P application rate was 70–90 kg P_2O_5 ha^{-1} in 31.8% of the areas, mainly distributed in the NE, northwest NC and south SW regions. The P fertilizer requirement of above 90 kg P_2O_5 ha^{-1} accounted for 11.1% of the study areas, mainly located in the NW region. It is noteworthy that P fertilizer application rate was less than 50 kg P_2O_5 ha^{-1} in 7.2% of the areas, mainly

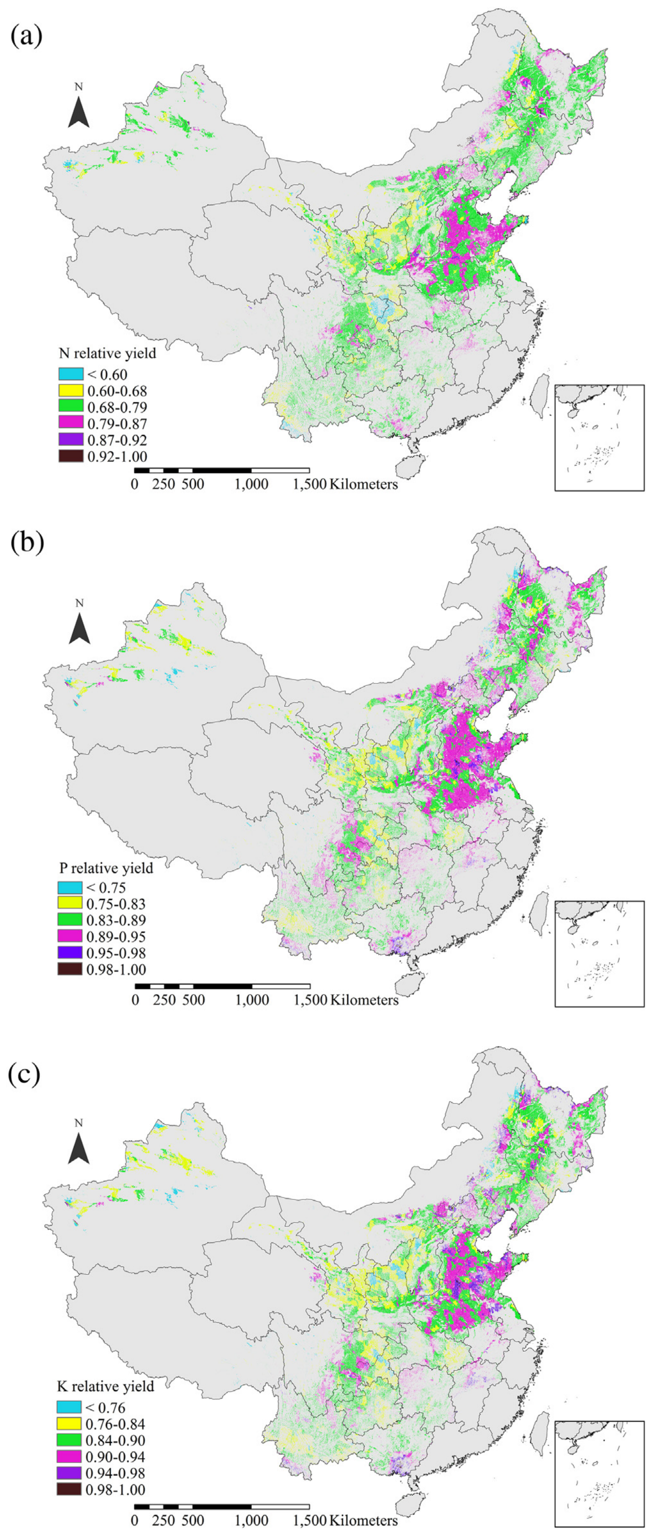

Fig. 3. Distribution of relative yield to N (a), P (b), and K (c) fertilizer for maize in China.

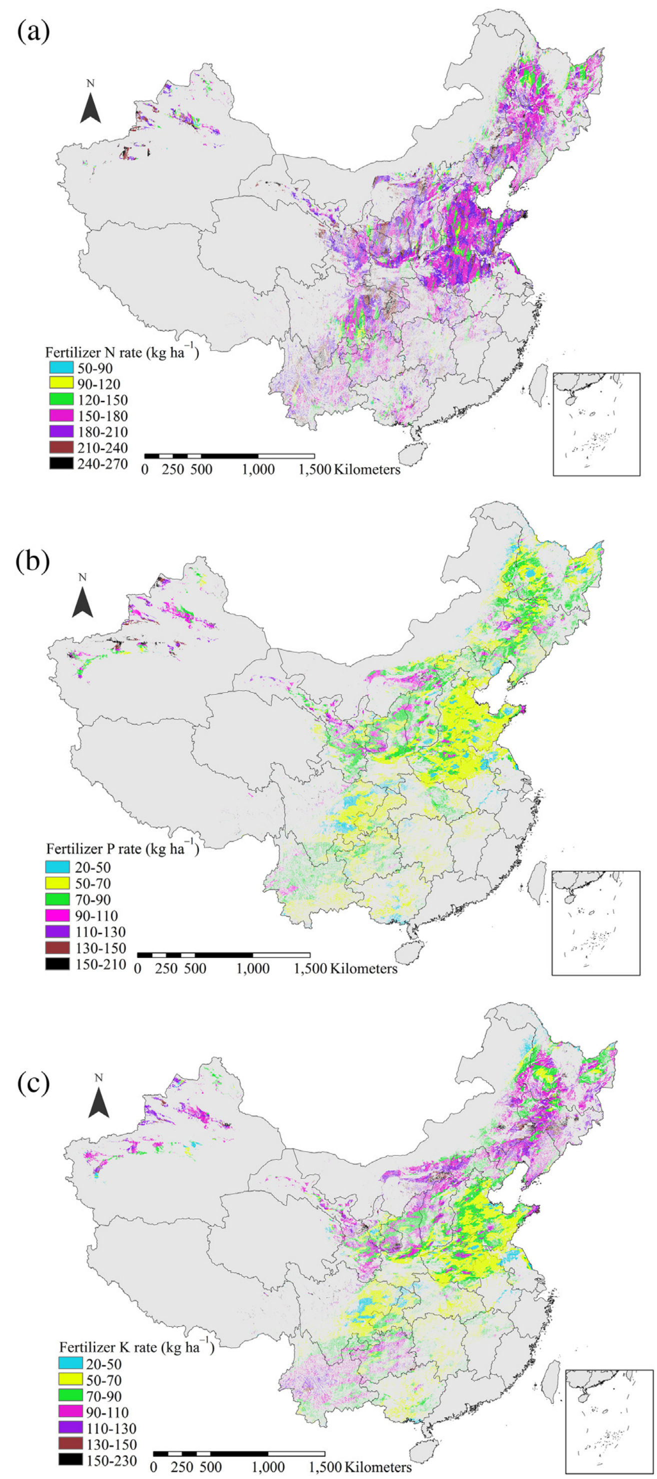

Fig. 4. Distribution of fertilizer N (a), P_2O_5 (b) and K_2O (c) requirements for maize in China.

distributed in the south NC and north MLYR regions, and in central Sichuan (SW region).

There was large variation in K fertilizer requirements among regions, with CV of 35.0% (Fig. 4c). The CVs were 27.4%, 30.6%, 36.2%, 39.2% and 31.6% for the NE, NC, NW, SW and MLYR regions, respectively. The K fertilizer requirement in central NC and MLYR, and north SW regions were lower than for other regions, with requirements of 50–90 kg K_2O ha^{-1} accounting for 57.8% of the study areas. The K fertilizer requirements of 90–110 kg K_2O ha^{-1} accounted for 23.7% of the areas, mainly in the NE, south NW and south SW regions. In 13.8% of the areas, the K fertilizer application rates exceeded 110 kg K_2O ha^{-1}, especially in the NE and NW regions; and more than 150 kg K_2O ha^{-1} was needed in some areas of Xinjiang. However, only 4.7% of the study areas had a K fertilizer requirement of less than 50 kg K_2O ha^{-1}.

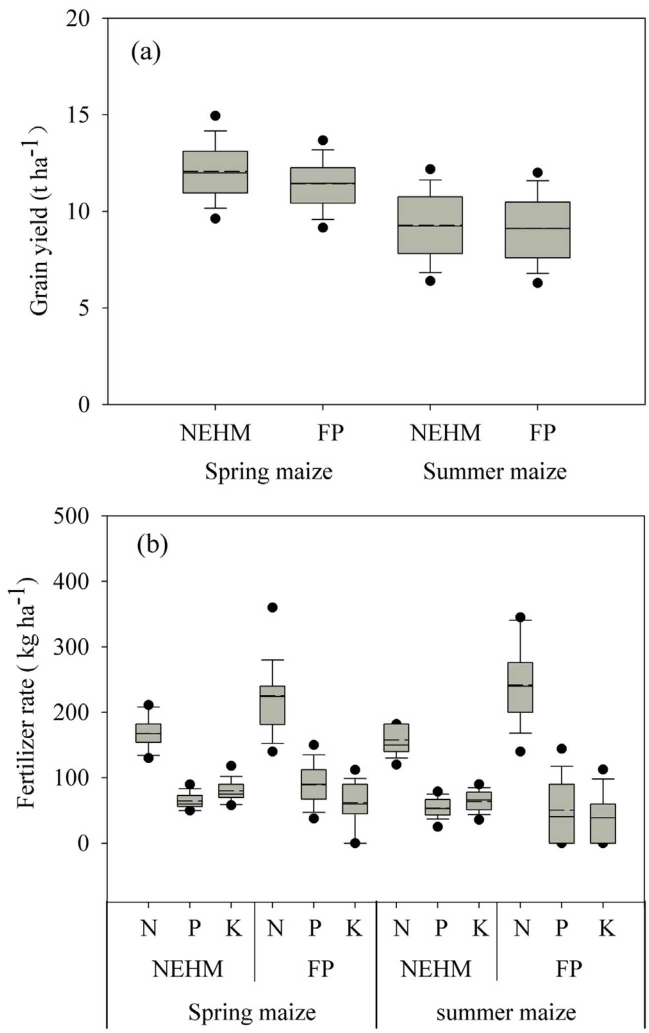

Fig. 5. The box plots of grain yield (a) and fertilizer application rate (b) of Nutrient Expert for Hybrid Maize (NEHM) system and farmers' practice (FP) for spring maize (n = 221) and summer maize (n = 384) in 2010–2014. N, P, and K represent fertilizer N, P_2O_5, and K_2O, respectively. Solid and dashed lines indicate median and mean, respectively. The box boundaries indicate the upper and lower quartiles, the whisker caps indicate 90th and 10th percentiles, and the circles indicate the 95th and 5th percentiles.

3.4. Field validation

There were 605 field experiments were conducted to validate the feasibility of the Nutrient Expert for Hybrid Maize in 2010–2014. The experimental fields covered 10 provinces located in the NE (Heilongjiang, Jilin and Liaoning), NC (Hebei, Henan, Shandong and Shanxi), NW (Ningxia), SW (Yunnan) and MLYR regions (An'hui). The average yields estimated by the Nutrient Expert system were 0.6 and 0.2 t ha^{-1} higher than the values for farmers' practices for spring and summer maize, respectively, representing increases of 5.7% and 1.7% (Fig. 5a). However, the Nutrient Expert estimates reduced N fertilizer by 25.8% and 34.7% relative to farmers' practices for spring and summer maize, respectively, and correspondingly decreased P fertilizer by 27.3% and 3.6%, and increased K fertilizer by 29.6% and 63.2% (Fig. 5b).

4. Discussion

Crop production in China must increase to meet future food requirements and strong competition for limited resources. Estimating AY at regional and national scales using data from previous field experiments is useful to inform decisions on policy, research and investment (Van Ittersum et al., 2013). For China as a whole, grain yield can be increased by 10% on average above current farmers' practices, through use of improved varieties, soil and nutrient management, and application of pest and weed control (Xu et al., 2015). Meng et al. (2013) found that the average AY was 12.3 t ha^{-1} using data from 137 field experiments, while the average farmers' yield was only 7.4 t ha^{-1}. In the current study, average AY was 9.9 t ha^{-1} and represented 65% of the potential yield (15.1 t ha^{-1}) simulated by Chen et al. (2011); ideally, the target AY should be within about 80% of the potential yield (Setiyono et al., 2010). However, maize yields became stagnated in 32.4% of maize-growing areas during 1980–2008 (Tao et al., 2015).

Long-term, multi-plot demonstrations and geospatial distribution of current AYs are needed to analyze spatial variability to reduce biased estimates and CVs, particularly for rain-fed regions (Lobell et al., 2009; Van Ittersum et al., 2013). In the current study, the AY varied among regions, with CV of 25.5%; the AY values from spring maize regions (NE, NW, southwest of SW and north of NC) were higher than those from the summer maize regions (NC plain, MLYR and northeast of SW). The differences in climate and rotation system were the major controls on the regional distribution differences for yield. For example, the long growing period in NE and NW compared with NC and MLYR (more than 40–50 days), and the higher day/night temperature difference may also help to accumulate dry matter.

Many studies suggest that the large yield gap between field experiments and farmers' yield is mainly related to inefficient crop management practices (He et al., 2009; Zhang et al., 2011; Meng et al., 2013). Meng et al. (2013) found that 63% of farmers applied too much or too little N fertilizer. Accounting for RY by using AY and yield responses to fertilizer application is important when estimating fertilizer requirements (Pasuquin et al., 2014). The RY can be used to represent the level of soil fertility, and high RY indicates a high soil nutrient supply capacity (Xu et al., 2014a). In the current study, the RY was higher in NC than other regions, which was related to high fertilization rate and straw returns. For intensive wheat–maize systems in North China, a typical N rates for farmers may exceed 500 kg ha^{-1} year^{-1} and even approach 600 kg N ha^{-1} year^{-1} (Cui et al., 2010), the net P surplus (the difference in input and output) may reach 53 kg ha^{-1} year^{-1} (Vitousek et al., 2009), while straw returns have helped to increase soil K concentrations (Zhao et al., 2014).

Chemical fertilizers play an important role in guaranteeing food security, and their usage in China has greatly increased since the 1990s (Fan et al., 2012). However, excessive fertilization has also led to a series of environmental problems (Ju et al., 2009). Overall, nutrient recovered by crop uptake form fertilizer applied to fields may be less than 50% and the rest is mostly released into the environment (Ju et al., 2009; Zhang et al., 2013). The average soil P content (Olsen) increased from 7.4 mg kg^{-1} in 1980 to 24.7 mg kg^{-1} in 2007 across China (Li et al., 2011). The high N surplus (N fertilizer applied in excess of uptake by crops) reached 72 kg N ha^{-1} in a survey of 5406 farmers' fields for maize systems in China (Chen et al., 2014). The average soil nitrate-N content in the uppermost 90 cm of the soil profile reached 190 kg ha^{-1} before maize sowing in the NC region (Cui et al., 2008b). Therefore, agricultural production still faces great challenges in increasing yields while reducing environmental costs in China.

Decreasing chemical input by balanced fertilization and nutrient management options to produce more grain with lower environmental costs is important to maintain future production (Chen et al., 2014; Wu and Ma, 2015). The RY was close to 1.0 in some areas in the current study (Fig. 3), indicating a high nutrient accumulation in soil which may lead to a minor yield response to fertilization. Results from region-wide experiments have demonstrated that the economically optimal N rate is 140–160 kg N ha^{-1} for maize in intensive wheat–maize systems (Cui et al., 2008b; Xu et al., 2014b), while 200 kg N ha^{-1} is needed for high yields (12–14 t ha^{-1}). In the current study, fertilizer recommendation based on the Nutrient Expert for Hybrid Maize not only reduced N (31.6%) and P fertilizer (15.5%) application rates, but also increased maize yield (3.3%) compared with farmers' practices across all experimental sites. The AY can show great variation using different methods; for a specific-site, a high AY indicates a high yield response and a high fertilizer requirement. Studies by Pampolino et al. (2012) and Pasuquin et al. (2014) showed that the Nutrient Expert for Hybrid Maize increased maize yield by 0.2–1.6 t ha^{-1} compared with farmers' practices in Philippines, Vietnam and Indonesia. A better N balance (savings of above 30% of applied N) can be achieved without sacrificing maize yield but significantly reducing environmental risk in China (Ju et al., 2009; Li et al., 2015).

Recently, the Chinese government announced an Action Plan on improvement of chemical fertilizer use efficiency through capping chemical fertilizer consumption by the year 2020, followed by initiating a National Key Research and Development Program on development of high-efficient fertilizer recommendation method and establishment of nutrient-limits standard. The public expectation is that the government needs to act, with a clear policy direction on controlling fertilizer increases in current farmers' practices and even establishing appropriate laws. According to the map distribution of soil fertility according to crop yield response, the government can develop a comprehensive program of auditing and reporting on the state of grain yields and soil nutrients, and regulate the supply of fertilizers to thus improve the ratio of resource utilization and protect the environment while guaranteeing grain supply.

Most current fertilizer recommendation strategies determine an average fertilizer need or single rate for a particular field or region. Forming geographic patterns of maize yield and fertilizer requirement using data for a large number of field experiments at regional levels is useful to quantify food production capacity and inform investment decisions (Van Ittersum et al., 2013). Fertilizer recommendation systems combined with geographical information systems provide a useful tool to identify how fertilizer requirements vary spatially in different fields or regions. Understanding spatial variability in yield, soil fertility and fertilizer requirements can help to guide technological development, and contribute to more efficient and effective fertilizer management. However, factors such as soil type, topsoil thickness, water and nutrient holding capacity and slope must be considered when formulating optimal management strategies to maintain sustainable and healthy agriculture.

5. Conclusions

By coupling geographical information systems and fertilizer recommendation systems with a large number of field experiments, we analyzed the spatial variability of AY, RY and fertilizer requirements across major maize production regions in China. We found large CVs in AY and RY within and between regions, which were related to climate, rotation system, fertilizer application and management. These heterogeneities were considered and integrated into crop management strategies in the Nutrient Expert for Hybrid Maize decision support system, and proved successful in making recommendations at the farm level. This method is a major step toward regional nutrient management and compilation of large on-farm trial databases to further refine the system, and will help provide a scientific basis for robust estimates of fertilizer recommendation at the regional level. However, an appropriate fertilizer recommendation system should also contain more detailed information on soil and climate information in each region, such as trace element supply intensities and water holding capacity, and respond constructively to climate change, to accurately simulate nutrient requirements at a national scale and achieve best nutrient management practices. If implemented correctly, yield benefits in China will be achievable with lower environmental costs at the farm, regional and national scales.

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References

Bélanger, G., Walsh, J.R., Richards, J.E., Milburn, P.H., Ziadi, N., 2000. Comparison of three statistical models describing potato yield response to nitrogen fertilizer. Agron. J. 92, 902–908.

Chen, X.P., Cui, Z.L., Vitousek, P.M., Cassman, K.G., Matson, P.A., Bai, J.S., Meng, Q.F., Hou, P., Yue, S.C., Römheld, V., Zhang, F.S., 2011. Integrated soil-crop system management for food security. Proc. Natl. Acad. Sci. U. S. A. 108, 6399–6404.

Chen, X.P., Cui, Z.L., Fan, M.S., Vitousek, P., Zhao, M., Ma, W.Q., Wang, Z.L., Zhang, W.J., Yan, X.Y., Yang, J.C., Deng, X.P., Gao, Q., Zhang, Q., Guo, S.W., Ren, J., Li, S.Q., Ye, Y.L., Wang, Z.H., Huang, J.L., Tang, Q.Y., Sun, Y.X., Peng, X.L., Zhang, J.W., He, M.R., Zhu, Y.J., Xue, J.Q., Wang, G.L., Wu, L., An, N., Wu, L.Q., Ma, L., Zhang, W.F., Zhang, F.S., 2014. Producing more grain with lower environmental costs. Nature 514, 486–489.

Cui, Z.L., Chen, X.P., Miao, Y.X., Li, F., Zhang, F.S., Li, J.L., Ye, Y.L., Yang, Z.P., Zhang, Q., Liu, C.S., 2008a. On-farm evaluation of winter wheat yield response to residual soil nitrate-N in North Chain plain. Agron. J. 100, 1527–1534.

Cui, Z.L., Zhang, F.S., Miao, Y.X., Sun, Q.P., Li, F., Chen, X.P., Li, J.L., Ye, Y.L., Yang, Z.P., Zhang, Q., Liu, C.S., 2008b. Soil nitrate-N levels required for high yield maize production in the North China Plain. Nutr. Cycl. Agroecosyst. 82, 187–196.

Cui, Z.L., Chen, X.P., Zhang, F.S., 2010. Current nitrogen management status and measures to improve the intensive wheat–maize system in China. Ambio 39, 376–384.

Dobermann, A., Witt, C., Abdulrachman, S., Gines, H.C., Nagarajan, R., Son, T.T., Tan, P.S., Wang, G.H., Chien, N.V., Thoa, V.T.K., Phung, C.V., Stalin, P., Muthukrishnan, P., Ravi, V., Babu, M., Simbahan, G.C., Adviento, A.A., Bartolome, V., 2003. Estimating indigenous nutrient supplies for site-specific nutrient management in irrigated rice. Agron. J. 95, 924–935.

Fan, M., Shen, J., Yuan, L., Jiang, R., Chen, X., Davies, W.J., Zhang, F., 2012. Improving crop productivity and resource use efficiency to ensure food security and environmental quality in China. J. Exp. Bot. 63, 13–24.

Greenwood, D.J., Karpinets, T.V., Stone, D.A., 2001. Dynamic model for the effects of soil P and fertilizer P on crop growth, P uptake and soil P in arable cropping: model description. Ann. Bot. 88, 279–291.

Guo, J.H., Liu, X.J., Zhang, Y., Shen, J.L., Han, W.X., Zhang, W.F., Christie, P., Goulding, K.W.T., Vitousek, P.M., Zhang, F.S., 2010. Significant acidification in major Chinese croplands. Science 327, 1008–1010.

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.

He, P., Yang, L.P., Xu, X.P., Zhao, S.C., Chen, F., Li, S.T., Tu, S.H., Jin, J.Y., Johnston, A.M., 2015. Temporal and spatial variation of soil available potassium in China (1990–2012). Field Crops Res. 173, 49–56.

Janssen, B.H., Guiking, F.C.T., van der Eijk, D., Smaling, E.M.A., Wolf, J., van Reuler, H., 1990. A system for quantitative evaluation of the fertility of tropical soils (QUEFTS). Geoderma 46, 299–318.

Ju, X.T., Xing, G.X., Chen, X.P., Zhang, S.L., Zhang, L.J., Liu, X.J., Cui, Z.L., Yin, B., Christie, P., Zhu, Z.L., Zhang, F.S., 2009. Reducing environmental risk by improving N management in intensive Chinese agricultural systems. Proc. Natl. Acad. Sci. U. S. A. 106, 3041–3046.

Li, H., Huang, G., Meng, Q., Ma, L., Yuan, L., Wang, F., Zhang, W., Cui, Z., Shen, J., Chen, X., Jiang, R., Zhang, F., 2011. Integrated soil and plant phosphorus management for crop and environment in China. A review. Plant soil 349, 157–167.

Li, Z.J., Hu, K.L., Li, B.G., He, M.R., Zhang, J.W., 2015. Evaluation of water and nitrogen use efficiencies in a double cropping system under different integrated management practices based on a model approach. Agric. Water Manage. 159, 19–34.

Lobell, D.B., Cassman, K.G., Field, C.B., 2009. Crop yield gaps: their importance, magnitudes, and causes. Annu. Rev. Environ. Resour. 34, 179–204.

Meng, Q.F., Hou, P., Wu, L., Chen, X.P., Cui, Z.L., Zhang, F.S., 2013. Understanding production potentials and yield gaps in intensive maize production in China. Field Crops Res. 143, 91–97.

Mueller, N.D., Gerber, J.S., Johnston, M., Ray, D.K., Ramankutty, N., Foley, J.A., 2012. Closing yield gaps through nutrient and water management. Nature 490, 254–257.

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. Agric. 88, 103–110.

Pasuquin, J.M., Pampolino, M.F., Witt, C., Dobermann, A., Oberthür, T., Fisher, M.J., Inubushi, K., 2014. Closing yield gaps in maize production in Southeast Asia through Site-specific nutrient management. Field Crops Res. 156, 219–230.

Robertson, M.J., Lyle, G., Bowden, J.W., 2008. Within-field variability of wheat yield and economic implications for spatially variable nutrient management. Field Crops Res. 105, 211–220.

Setiyono, T.D., Walters, D.T., Cassman, K.G., Witt, C., Dobermann, A., 2010. Estimating maize nutrient uptake requirements. Field Crops Res. 118, 158–168.

Simmonds, M.B., Plant, R.E., Peña-Barragán, J.M., Van kessel, C., Hill, J., Linquist, B.A., 2013. Underlying causes of yield spatial variability and potential for precision management in rice systems. Precision Agric. 14, 512–540.

Sonar, K.R., Babhulkar, V.P., 2002. Application of Mitscherlich–Bray equation for fertilizer use in wheat. Commun. Soil Sci. Plant Anal. 33, 3241–3249.

Tao, F.L., Zhang, S.A., Zhang, X., Rötter, R.P., 2015. Temporal and spatial changes of maize yield potentials and yield gaps in the past three decades in China. Agric. Ecosyst. Environ. 208, 12–20.

Tsirulev, A., 2010. Spatial variability of soil fertility parameters and efficiency of variable rate fertilizer application in the Trans-Volga Samara region. Better Crops 94, 26–28.

Van Ittersum, M.K., Cassman, K.G., Grassini, P., Wolf, J., Tittonell, P., Hochman, Z., 2013. Yield gap analysis with local to global relevance—a review. Field Crops Res. 143, 4–17.

Vitousek, P.M., Naylor, R., Crews, T., David, M.B., Drinkwate, L.E., Holland, E., Johnes, P.J., Katzenberger, J., Martinelli, L.A., Matson, P.A., Nziguheba, G., Ojima, D., Palm, C.A., Robertson, G.P., Sanchez, P.A., Townsend, A.R., Zhang, F.S., 2009. Nutrient imbalances in agricultural development. Science 324, 1519–1520.

Wang, Y.Q., Zhang, X.C., Huang, C.Q., 2009. Spatial variability of soil total nitrogen and soil total phosphorus under different land uses in a small watershed on the Loess Plateau, China. Geoderma 150, 141–149.

Wu, W., Ma, B.L., 2015. Integrated nutrient management (INM) for sustaining crop productivity and reducing environmental impact: a review. Sci. Total Environ. 512–513, 415–427.

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., 2014a. 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., 2014b. 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, S.C., Qiu, S.J., Zhou, W., 2015. Yield gap, indigenous nutrient supply and nutrient use efficiency for maize in China. PLoS One 10, 1–12.

Zhang, F.S., Cui, Z.L., Fan, M.S., Zhang, W.F., Chen, X.P., Jiang, R.F., 2011. Integrated soil–crop system management: reducing environmental risk while increasing crop productivity and improving nutrient use efficiency in China. J. Environ. Qual. 40, 1051–1057.

Zhang, F.S., Chen, X.P., Vitousek, P., 2013. An experiment for the world. Nature 497, 33–35.

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 Res. 169, 116–122.