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REVIEW

The transformation of agriculture in China: Looking back and looking forward

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Abstract
China's grain yield increased from 1 t ha^{-1} in 1961 to 6 t ha^{-1} in 2015, while successfully feeding not only its large population but also supplying agricultural products all over the world. These achievements were greatly supported by modern technology and distinct governmental policy. However, China's grain production has been causing a number of problems mainly related to declining natural resources and a lack of environmental protection. Due to the growing population and changing dietary requirements, increasing food production must be achieved by increasing resource use efficiency while minimizing environmental costs. We propose two novel development pathways that can potentially sustain agricultural crop production in the next few decades: (i) enhancing nutrient use efficiency with zero increase in chemical fertilizer input until 2020 and (ii) concurrently increasing grain yield and nutrient use efficiency for sustainable intensification with integrated nutrient management after 2020. This paper provides a perspective on further agricultural developments and challenges, and useful knowledge of our valuable experiences for other developing countries.

Keywords: food security, sustainable development, agriculture, grain production

1. Introduction

Due to Borlaug's Green Revolution, China has successfully produced enough grain for its large population while using only 9% of the global arable land during the past half century (Zhang 2011). Without this revolution, it is very likely that this comparably small amount of land would not have sustained China's growing population and would have led to many serious problems as a result of starvation (Brown 1995). Currently, grain per capita is more than 400 kg in China. In addition, China has become one of the largest agricultural producers. The high food production helped reduce a number of social problems resulting from hunger and food shortages in China. For example, the public now has greater access to grain at reasonable and stable prices (Khush 2001; Pingali 2012). In addition, China was the first developing country to achieve the target of reducing poverty in the population by half in 2015 (Huang and Yang 2017). Overall, the agricultural industry has made significant contributions to the economic development of China since the establishment of the People's Republic of China in 1949.

Farmers in the agricultural sector still have challenges to

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face in the next few decades, such as continuing to improve grain production while reducing chemical fertilizer application and improving protection of the environment (Tso 2004; Fan *et al.* 2012; Shen *et al.* 2013). Average grain yield in China was only half the size of that in the EU and USA in 2005. Furthermore, grain production stagnated or declined in a large proportion of the arable land in China during the last few decades, due to inappropriate agronomy practices, climate change and so on (Ray *et al.* 2012). Compared with other developed economies, grain production in China utilized more resources, such as chemical fertilizer, to achieve high yields (Vitousek *et al.* 2009; Jiao *et al.* 2016). Indeed, China produced 19% of the world's food supply while using an amount of chemical fertilizer equivalent to 30% of the world's annual food consumption during the last decade (West *et al.* 2014; Jiao *et al.* 2016). Excessive use of chemical fertilizers causes many negative environmental impacts, such as water pollution, eutrophication, high NO_3^- concentration in underground water and air pollution (Carpenter 2008; Liu *et al.* 2013; Norse and Ju 2015; Zhou *et al.* 2016).

Sustainable agriculture has become the new focus of research in China. In fact, food security has become a high priority to the Chinese government and is thus, closely regulated by policy, particularly in economic and social fields. In 1980, China's government introduced the Household Responsibility System to replace the People's Commune System, which stimulated farmers' enthusiasm to farm. Moreover, until 2015, the Chinese government has released 14 "No. 1 Documents" focusing on agriculture (Tong *et al.* 2003; Yang 2006; Jiao *et al.* 2016). This declaration has objectives for promoting grain production and reducing the use of natural resources by facilitating more technological advances in this area. However, it is difficult to develop feasible strategies that will achieve sustainable grain production while overcoming so many challenges. This begs the question: can China produce a sufficient food supply to feed its growing population while protecting the environment and preserving its limited natural resources?

In this study, we examined the trends of grain yield in China during the past half-century, and then identified the factors that contributed to grain yield increase, such as technological advances and policy support. Next, we focused on the challenges and problems of grain production in China during the last decade. Finally, we addressed potential pathways for sustainable intensification in agriculture for China's future.

2. Historical dynamic trajectory of grain production in China over the past half-century

During the phenomenon nationally known as the "Miracle", China's agricultural producers were feeding 22% of the world's population despite using only 9% of the world's arable land (Fan *et al.* 2012). Grain production per capita in China increased dramatically from less than 250 kg in the 1960s to more than 400 kg in the 2010s (Zhang 2011). In the past half-century, grain yield increased steadily from 1 t ha^{-1} in 1961 to 6 t ha^{-1} in 2015 (Fig. 1). In comparison with other countries, China's grain yield, at its lowest in 1961, was equivalent to Africa's grain yield in 2005. China's grain yield then increased to 3 t ha^{-1} by 1980, when it achieved the same level as Latin America and South-East Asia in 2005 (Sanchez 2015). In 2015, grain yield in China peaked at 6.0 t ha^{-1}. The likely cause of China's "Miracle" is the use of technological innovations such as chemical fertilizers, semi-dwarf and heterotic crops, and pesticides, in conjunction with the introduction of better policies and regulations by the Chinese government (Zhang 2011; Huang and Zhang 2017).

Today, agriculture is an industry of food, fiber and energy production based on the growth and development of plants to sustain and enhance human life (Oenema *et al.* 2009). It is like a converter that combines the inputs of solar radiation, CO_2, water and soil nutrients and transforms them into food for human and other animal consumption. The four inputs are the key elements of the agricultural converter. China's "Miracle" of feeding 22% of the world population with 9% of the world's arable land was due to China's effective integration of all these elements based on increasing scientific knowledge of the intricacies of plant-soil interactions for grain production during the past half century (Yang 2006; Fan *et al.* 2012).

Generally, agricultural soil in China was considered not fertile enough to improve grain production (Yang 2006). However, many approaches have been used to improve soil quality such as application of manure, chemical fertilizer and crop straw return (Yang 2006). Yang (2006) estimated that about 90 kg ha^{-1} of manure and 40 kg ha^{-1} of chemical fertilizer were applied into croplands in China in the 1970s. Farmers in rural areas call manure "organic treasures". Manure is typically collected from domestic animals, such as pig, cattle, and poultry. The animals feed on crop residuals, weeds, and grasses and their feces are then recycled as fertilizer to improve soil fertility (Li *et al.* 1988). Most importantly, manure applied to soil can stimulate plant growth, and in turn, result in more root carbon (root biomass carbon and rhizo-deposition carbon) return to the soil for maintaining fertility. This positive feedback loop with manure to sustainably maintain soil fertility has been integrated with other agronomic practices as a basic strategy to increase grain production (Barrett and Bevis 2015; Vanlauwe *et al.* 2015).

Chemical fertilizers, especially N-enriched fertilizers, were widely used by farmers to boost crop yield in the 1980s

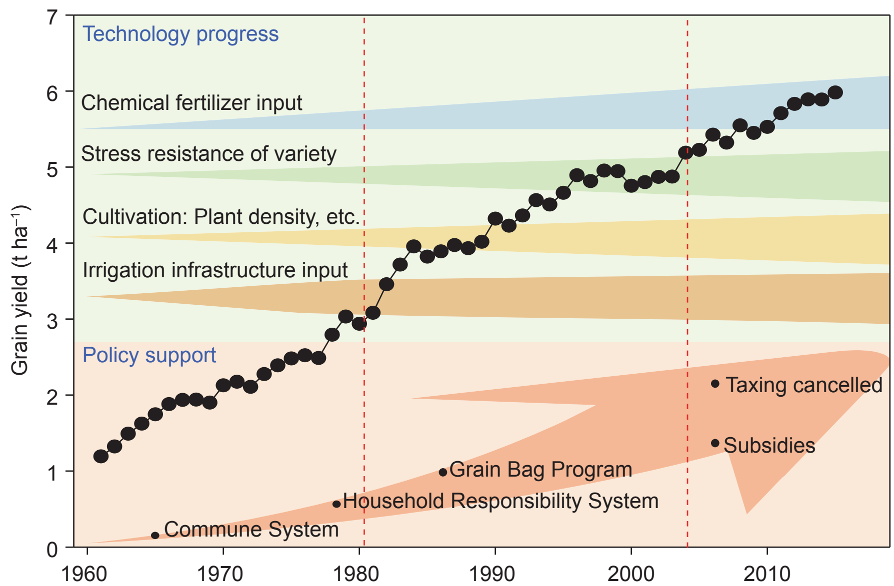

Fig. 1 The technological progress and policy support for grain production from the 1960s to the 2000s in China. Grain yield represents average yield of maize (*Zea mays*), wheat (*Triticum aestivum*), rice (*Oryza sativa*), barley (*Hordeum vulgare*), buckwheat (*Fagopyrum esculentum*), millet (*Pennisetum glaucum*), rye (*Secale cereale*), sorghum (*Sorghum bicolor*), and triticale (*Tritico secale*). Data are from FAOSTAT database (FAO 2015). The red dashed lines represent 3 and 5 t ha^{-1} grain yield achieved in 1980 and 2004, respectively. Different colors of triangle strips represent different agricultural inputs. The thickness of each strip under different historical periods indicates the relative size of the agricultural input.

(Yang 2006). Chemical fertilizers supplement nutrients for crops and can help maintain soil fertility in nutrient-depleted soils. Farmers applied an estimated 20 Mt of chemical fertilizer in the 1980s and more than doubled the amount to 43 Mt in 2004 (IFA 2017). Jiao *et al.* (2016) observed a positive linear relationship between grain production and chemical fertilizer application in the 1980s and 1990s. In on-farm trials in South China, Fan *et al.* (2013) observed soil productivity in rice field plots had increased from 0.7 t ha^{-1} in the 1980s to 1.8 t ha^{-1} in the 2000s. Many other studies on crops like wheat and maize, came to similar conclusions (Su 2012). Therefore, the grain yield increase between 1980 and 2004 is likely a result of increasing use of chemical fertilizers since the 1980s (Fig. 1).

Another significant method used to improve grain yield was genetic modification of crop varieties after the 1960s (Zhang *et al.* 2003). Heterosis, played a significant role in grain yield improvement (Katsura *et al.* 2007; Zhang 2011). Examples of heterosis are found in the semi-dwarf traits in rice and wheat that were widely planted in China in the 1970s (Gaud 1968; Wang *et al.* 2010). As farmers used a greater supply of water and chemical fertilizers in their fields, these conditions favored the height of semi-dwarf plants over the too-short dwarf wheat variety and too-tall normal wheat variety (Khush 2001). In another example, the single-cross hybrid maize, which is characterized by disease-resistance and stay-green and erect leaves (Khush 2001; Li and Wang 2009), was planted extensively in the 1980s. Those traits allowed the hybrid maize to be planted densely. Another beneficial trait was found in rice. Yuan Longping, a well-known agricultural scientist in China, found a male sterile trait in wild rice that he bred into cultivated rice (Yuan 1992; Zhang 2011). Compared with conventional rice, the hybrid rice produced less but sturdier tillers, and a higher number of grains per panicle (Khush 2001). Yield potential of this hybrid rice was 25% higher than the conventional cultivars (Zhang 2011).

In the last decade (2005–2015), modern crop varieties and improved agronomic practices have made significant contributions to grain yield improvement (George 2014). High-yield crop varieties, such as density-tolerance maize and disease-resistance rice, became widely used in agricultural practice. In addition, many advanced agronomical practices included more tools, such as soil-testing, delaying harvesting strategies, and crop straw returning (Liu *et al.* 2015). Farmers shifted from applying individual techniques to applying more novel integrated programs (Zhang *et al.* 2016). For example, farmers only use chemical fertilizer to improve grain yield in the 1980s, while in the 2000s, the Integrated Nutrient Management (INM) Program, which combines chemical fertilizer use with cultivations, was broadly used by farmers (Fan *et al.* 2012). In some areas of North China Plain, grain yield was as high as 8 t ha^{-1} after more farmers adopted new agronomic technologies (Zhang *et al.* 2016). All of these approaches increased crop yield rapidly.

Besides the technological advances in agriculture, policy support was the most crucial component to promote the use of technology as well as incentivize farmers to strive for high-yield grain production (Huang and Yang 2017). The Chinese government began prioritizing the issue of food security by enacting several policies during the half-past century. Farmers managed state-owned arable lands in collectivized farms under the auspices of the People's Commune System for grain production in China from 1961 to 1978 (Zhang 2011; Jiao *et al.* 2016). This government policy alleviated the country's famine to some extent, despite resource limitations. However, the approach was notoriously ineffective for grain production. Consequently, in 1978, a new policy called the "Household Responsibility System" was introduced by the government, which allocated each household a plot of land for farming. This new policy of land contracts completely changed the attitudes of farmers for farming (Zhang 2011). Under this policy, farmers could produce more grain than public demand by increasing chemical fertilizer use, and prolonging working hours on farms. However, low grain prices in the 1980s diminished farmers' enthusiasm to produce. In 1985, the Chinese government encouraged farmers to bring the surplus grain to market for sale at a reasonable price. This aroused farmers' creativity and enthusiasm for production again. Thus by 2004, grain yield increased from 3 to 5 t ha^{-1}. In 2004, the government removed a long-standing policy of taxing farm households and began to provide farmers with subsidy payments, such as "grain subsidy," "input subsidy," "quality seed subsidy," and "agricultural machinery subsidy" to encourage grain production (Huang *et al.* 2011). With the help of this latest policy, grain yield improved again, from 5 t ha^{-1} in 2004 to 6 t ha^{-1} in 2015.

3. Challenges and problems of grain production in China during the last decade

Compared with the developed economies, such as the EU and USA, grain production in China needs improvement (Ray *et al.* 2012; Zhang *et al.* 2015). For example, in 2005, grain yield in the EU and USA was about 10 t ha^{-1}, whereas, in China was less than half of these western countries (Sanchez 2015). Furthermore, an increase in grain yield was not observed in 79% of rice, 56% of wheat, and more than 50% of maize farmland in China between 1961 and 2008 (Ray *et al.* 2012). Poor agronomy practices may explain the low and relatively static grain yield (George 2014). The efficiency of using agricultural technology in small-holder farming was quite low due to high variability among fields and poor extension of service infrastructure (Zhang *et al.* 2016). In some areas, most farmers lacked an education on how much N-fertilizer to apply to obtain optimal amounts of grain production. Consequently, they supposed that applying more N, regardless of how much a crop needed, was an "insurance" strategy against low yields. Instead, they inadvertently added superfluous amounts of N into the soil that polluted their water resources (Vitousek *et al.* 2009; Zhang *et al.* 2016).

Yield gap, defined as the difference between yield potential and the actual yield obtained by farmers, is heavily controlled by fertilizer use and irrigation. Mueller *et al.* (2012) estimated that an approximate increase of 30% in production of major cereals (maize, wheat and rice) could be obtained by improving water and nutrient management. In China's intensive farming systems, crop yield has failed to increase regardless of the high chemical fertilizer consumption since 2005, possibly indicating low nutrient-use efficiency due to over-fertilization (Zhang *et al.* 2010; Lassaletta *et al.* 2014). Excessive fertilization in China's major cropland is very common (Vitousek *et al.* 2009; West *et al.* 2014) because of the false assumption that high input equals high output that was also supported by the government (Zhang *et al.* 2010; Shen *et al.* 2013; Withers *et al.* 2014). Consequently, the amount of chemical fertilizer added to farmland grew disproportionately higher than the amount of grain produced. During the last decade, China produced 19% of world grain production with 29% of chemical fertilizer use, at the same time the USA was responsible 16% of global grain with 12% of world's chemical fertilizer consumption (Jiao *et al.* 2016). Indeed, N use efficiency was only 30% of the USA (Vitousek *et al.* 2009). Excessive fertilization has resulted in huge amount of nutrients left in croplands during the last few decades (MacDonald *et al.* 2011). It was estimated that more than 70% of the cropland suffered from excess synthetic N use in North China Plain (receiving 2–3 times more N than a crop needs) (Ju *et al.* 2009). For instance, in the North China Plain, the total N demand by crops was 361 kg ha^{-1}, while the total N input by farmers was 588 kg ha^{-1}, leaving 227 kg N ha^{-1} in the cropland annually. Furthermore, on average from 1980 to 2007, 242 kg P ha^{-1} accumulated in China's croplands. Consequently, average plant available P has increased from 7.4 to 24.7 mg kg^{-1} (Li *et al.* 2011). According to a predicted model produced by the Dynamic Phosphorus Pool Simulator (DPP), the amount of P accumulated in major cropland areas in China was equivalent to half of the P required in Africa or sufficient for Western Europe to achieve its target crop P uptake in 2050 (Sattari *et al.* 2014).

Inevitably, nutrient imbalance has resulted in serious environmental degradation (Sutton *et al.* 2011). For example, about 50% of lakes investigated in China were in an eutrophic state due to excessive nutrient supply, especially P (Jin *et al.* 2005; Carpenter 2008). Since the 1980s, the average annual bulk deposition of N has increased by approximately 8 kg ha^{-1}. In the 2000s, 21.1 kg N ha^{-1} from N deposition was observed in farmland, which was three to four times higher than that in the UK (Goulding *et al.* 1998; Liu *et al.* 2013). Furthermore, excessive N fertilization contributed substantially to soil acidification. Compared with the soil conditions in the 1980s, soil pH in China's major croplands declined by 0.5 in the 2000s. A lower pH is a major threat to soil health for grain production (Guo *et al.* 2010; Zeng *et al.* 2017). In addition, greenhouse emissions in China during the last decade was about 3-fold higher than developed countries, such as the EU and USA (Jiao *et al.* 2016; Zhang *et al.* 2017). Therefore, China's agriculture became an example of poor mismanagement of a system that lead to excessive nutrient inputs, low grain yield, and high greenhouse gas emissions (Oenema *et al.* 2009; Lu *et al.* 2011). These negative consequences are warnings to us to manage, more sensibly, all resources while aiming for sustainable grain production in China.

4. Implications and perspective

During the past half century, grain yield in China exhibited a steady linear increase from 1 t ha^{-1} in the 1960s to 6 t ha^{-1} in the year 2015 because of the support from the government and technological progress. Concurrently, there was a 10-fold increase in N fertilizer, 30-fold increase in P fertilizer and 6-fold increase in irrigation of land for the improvement of grain production (Zhang *et al.* 2011). However, in order to conserve natural resources, such as land and water, and minimize environmental impacts, improvement of nutrient use efficiency will be crucial in grain production in the next few decades (Zhang F S *et al.* 2014). Therefore, we need to introduce adaptable agronomic strategies and regulations that considering environmental protection to meet the target of sustainable agriculture. Two key approaches are necessary to address these challenges (Fig. 2): (i) enhancing nutrient use efficiency with a zero increase in chemical fertilizer input and (ii) increasing grain yield and nutrient use efficiency simultaneously for sustainable intensification with integrated nutrient management.

4.1. Enhancing nutrient use efficiency with zero increase in chemical fertilizer input

Chemical fertilizer is crucial to increasing grain yield and thus, has been accepted by farmers for use in grain production since it was introduced in China in the 1960s (Tong *et al.* 2003). For over 50 years, farmers in China have been encouraged by the government to use chemical fertilizers to maintain soil fertility and maximize crop outputs

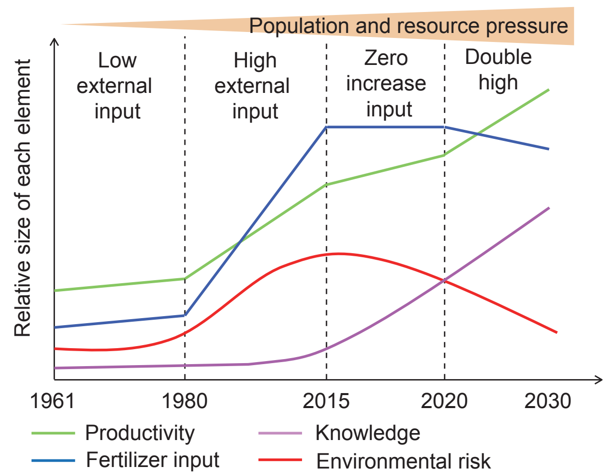

Fig. 2 Historical and projected patterns of grain production in China. This figure was divided into four sections (low external input, high external input, zero increase input and double high) in the periods between 1961 and 2030 according to the external inputs. Low external input, high external input and zero increase input means low, medium and high chemical fertilizer input, respectively. Double high represents to optimize chemical input and improve grain yield.

(Withers *et al.* 2014). Chinese farmers believe that it is a good practice to use more fertilizer to increase the soil nutrient concentration to achieve higher grain yields (Drinkwater and Snapp 2007; Gao *et al.* 2012). Therefore, over-fertilization commonly occurred in a vast majority of China's croplands in the last decade (Ju *et al.* 2009; Cui *et al.* 2014). In North China Plain, soil NO_3-N concentration in the root zone was around 180 kg N ha^{-1} due to excessive N supply. The amount of residual N in the soil could support 8 t ha^{-1} maize yield (Cui *et al.* 2013). Similarly, in Northeast Plain of China, maize yield without N fertilization was on average 7.6 t ha^{-1}, indicating that soil residual N could support 80% of the N demand of maize annually (Gao *et al.* 2012). The large amount of nutrients that have accumulated in soils is a potential nutrient pool that can be utilized by crops if they are managed appropriately. Instead, this nutrient pool is causing a wide range of environmental problems, such as water eutrophication, nitrate leaching and ammonia volatilization (MacDonald *et al.* 2011; Sattri *et al.* 2012).

Previous research suggests that plants can use the nutrient pool without any losses in yield (Ju *et al.* 2009; Satarri *et al.* 2012). For instance, use of chemical N fertilizer was reduced by 30–60% without influencing grain yield in wheat-maize rotation in North China Plain and wheat-rice rotation in the Taihu Lake region in the 2000s (Ju *et al.* 2009; Peng *et al.* 2010; Cui *et al.* 2014). Similar results were obtained in P management cases. In wheat-rice rotation, rice yield was maintained despite a reduction of chemical

P fertilizer by 50% over four years (Wang *et al.* 2016). Evidence at regional or county scales have also exhibited similar findings that soil nutrient pools could be used in cropping systems without any losses in yield (Kamprath 1967; Sattari *et al.* 2012; Jiao *et al.* 2016). For example, in Japan, crop yields remained constant or even increased, despite a decline in use of P fertilizer and manure between 1985 and 2005 (Mishima *et al.* 2010). In the EU, grain yield initially increased with fertilizer application. However, the level of yield still remained the same after chemical fertilizer use declined since the 1980s, which suggests a residual nutrient pool may have been present in the soil (Sattari *et al.* 2012; Jiao *et al.* 2016). Residual nutrient pools have the potential use of reducing the need to add more chemical fertilizer, until the pools run out.

High soil nutrient concentration due to excessive fertilization could possibly sustain plant growth for several years without further applications of fertilizer because of how plants naturally respond to their environments (Lynch 2011; Deng *et al.* 2014; Bender *et al.* 2016). For example, plants may change their root growth pattern (root elongation, branching and root hairs) to enhance exploration of the soil to acquire nutrients, such as phosphorus and water (Lynch 2011). Another important plant mechanism to acquire soil accumulated-P is that plants can release protons, carbon substrates and enzymes within the rhizosphere to increase mobilization of soil inorganic and organic-P (Shen *et al.* 2013). Besides altering root morphological and physiological growth patterns, plants can affect microorganisms' structure and functions to enhance efficiency of plant nutrient acquisition (Zhang L *et al.* 2014). For example, mycorrhizae or phosphate-solubilizing bacteria living in the rhizosphere make soil-P available for plant roots to uptake. In addition, high soil nutrient concentrations can inhibit root growth to some extent (Shen *et al.* 2013). For instance, under high N supply, root length was reduced significantly in field-grown maize. When soil-N concentration was reduced, root growth increased (Shen *et al.* 2013).

In 2015, the Ministry of Agriculture of China launched the campaign on "Zero Growth" Program of fertilizer input by 2020 (Liu *et al.* 2015). The campaign's objective was to cap the use of chemical fertilizers below one percent of chemical fertilizer use in 2015 until 2019, with no further increase slated for 2020 without any yield losses. Results from thousands of field experiments conducted by China Agricultural University from 2005 to 2015 gave strong support for the "Zero Growth Action Plan" Program (Ju *et al.* 2009; Hvistendahl 2010). The Chinese government will invest a total of $800 million USD to support the implementation of the N Fertilizer "Zero Growth Action Plan" in different regions and for various crops across China in the next five years (2015–2020). Many approaches to improve N-use efficiency, such as optimizing fertilization application rates, optimizing chemical fertilizer proportions of N, P and K, improving fertilization techniques and increasing organic fertilizer application to replace chemical fertilizers, were recommended by the Chinese government for increasing grain production while mitigating environmental risk (MOA 2015).

4.2. Increasing grain yield and nutrient use efficiency simultaneously for sustainable intensification with integrated nutrient management

Population growth, changing diets, and changing attitudes toward environmental protection have posed greater challenges to the future development of agriculture in China. Population growth inevitably leads to having more mouths to feed. Due to greater economic development, Chinese diet preferences have shifted towards consumption of more refined sugars, refined fats, oils and meats. This dietary transition has become a major contributor to greenhouse gas emissions because it requires greater amounts of food production and land clearing (Tilman and Clark 2014). Because of China's growing awareness and prioritization of environmental protection, agricultural producers must supply sufficient food to feed the growing population and its new diet preferences while ensuring that their agricultural practices also reduce potential negative impacts on the environment. Increasing crop production while decreasing fertilizer inputs by implementing more efficient nutrient-use strategies is one of the major future directions in agricultural development (Zhang *et al.* 2013; Chen *et al.* 2014). However, compared with developed economies, such as the EU and USA, grain yield in China is still low. In addition, China's disproportionate consumption of chemical fertilizer has left abnormally high amounts of nutrients in croplands. The surplus of nutrients has caused serious environmental harm, such as water eutrophication, air pollution, biodiversity loss, and more (Carpenter 2008; Sutton *et al.* 2011; Liu *et al.* 2013). Therefore, we face many difficult challenges and should integrate environmental management plans with farming practices to build a more comprehensive agricultural system that can overcome these hurdles in improving grain yield.

Agronomy is a very complex multidisciplinary science that integrates all fields, such as soil, plant and weed sciences, genetics, ecology, entomology, pathology for grain production (ASA 2013). To achieve the target of "produce more with less" in the future, it is necessary to integrate a wide range of methods and practice agronomy with a finer level of precision in large farms fields. Such methods include but not limited to: pre-plant lands, improving crop and planting date decisions to optimize for post-harvest reside and crop rotation management (Chen *et al.* 2014). China Agricultural University developed an approach called the Integrated Soil-crop System Management (ISSM) approach based on past high nutrient input and high grain output systems. However, with this approach, applied research is used to help us understand the mechanisms between plant demand and soil nutrient supply by involving three key elements towards grain production. The key elements in this approach are: (i) taking all possible measures for improving soil quality; (ii) integrating crop nutrient requirements with nutrient application at both spatial and temporal scales; and (iii) integrating soil and nutrient management in high-yield fields (Zhang *et al.* 2011).

Since 2006, the ISSM approach was tested in China's major croplands (Chen *et al.* 2011). This experiment using 66 on-farm plots in North China Plain found that mean maize yield in plots grown using the ISSM approach was 13.0 t ha^{-1}, which was twice as high as the yield observed in plots using conventional practices, without any increase in chemical fertilizer use. In these field trails, partial fertilizer productivity (the ratio of crop yield per unit of applied N fertilizer) was 30 kg kg^{-1} using conventional practices, while it was as high as 68 kg kg^{-1} with ISSM (Zhang *et al.* 2011). Based on 153 field experiments conducted in different ecological zones of China, 1.3, 1.7, and 3.7 t ha^{-1} yield gaps were observed in rice, wheat, and maize, respectively, in terms of improvement of nutrient management and agronomic practices with ISSM (Chen *et al.* 2014). Furthermore, reactive nitrogen losses and greenhouse gas emissions were reduced substantially because of the application of ISSM. Chen *et al.* (2014) predicted that if farmers in China increase average grain yield by 80% of the yield potential from 2012, then food production can sufficiently feed the growing Chinese population by 2030. Moreover, environmental cost for grain production could be substantially reduced (Chen *et al.* 2014). Other countries, such as the US, have successfully achieved high-yields in maize with high net energy yield while contributing little negative impacts to global warming (Grassini and Cassman 2012). The research up to now reinforces our endeavors to achieve higher grain yields while reducing environmental harm by enhancing nutrient use efficiency in China.

Unfortunately, the adoption of the ISSM Program by farmers has been a challenge. Many farmers across China are unable to obtain updated agricultural information due to the lack of appropriate extension services (Baulcombe *et al.* 2009; George 2014). Indeed, a vast majority of farmers is still struggling to use chemical fertilizers appropriately; most commonly, errors are made in applying the appropriate N doses for high-yield maize production. Therefore, China Agricultural University established the Science and Technology Backyards (STB) Program to improve knowledge transfer of agricultural advances to farmers. The STB is composed of a large number of students and professors who are experienced in conducting research-education extension activities that focus on technology-transfer for sustainable intensification of food production and empowerment of farmers (Zhang *et al.* 2016). Most farmers have accepted the technology of ISSM because, compared with farmers without any training, ISSM-trained farmers have increased their grain yield by 30% and nutrient use efficiency by 50% (Zhao *et al.* 2016). Grain yield in Quzhou, a typical agricultural county in North China Plain, increased from 5 to 8 t ha^{-1} after the technology of ISSM was accepted in the whole county (Zhang *et al.* 2016).

5. Conclusion

Chinese grain yield increased from 1 t ha^{-1} in 1961 to 6 t ha^{-1} in 2015. Producers successfully provided a sufficient food supply for China's rapidly growing population because of technological advances and policy support in agriculture. However, the country must now contend with the unfortunate side effects of growth development: overconsumption of resources and negative environmental impacts. Additionally, rapid increases in population and its corresponding food needs and changing diets create new challenges for China's agricultural sector to face. To cope with these challenges, we proposed a multidisciplinary, two-pronged approach to achieve sustainable crop production in the next few decades: (i) enhancing nutrient use efficiency with zero increase in chemical fertilizer consumption from 2015 to 2020 and (ii) increasing grain yield and nutrient use efficiency simultaneously for sustainable intensification with integrated nutrient management after 2020.

There is no simple solution to the challenges faced by future agricultural development. The innovative trajectories of agricultural development must effectively increase crop production while minimizing negative environmental impacts by improving resource use efficiency. Altogether, these goals create a monumental challenge that many countries still face today. Nevertheless, China can benefit from the experiences of developed economies, such as the EU and USA, and it can also be an example for developing countries facing similar challenges, such as India, Bangladesh and Africa.

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