Grain production versus resource and environmental costs: towards increasing sustainability of nutrient use in China

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Running title: Grain production vs resource-environmental costs: towards sustainable nutrient use

With 6858 words, 7 figures (All figures should be published in color)

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Highlight (30 words)

We analyzed the recent advances in China’s crop production versus resource and environmental costs, highlighting approaches to underpin sustainable nutrient use and increased grain production in the future.

Abstract

Over the past five decades, Chinese grain production has increased 4-fold, from 110 Mt in 1961 to 557 Mt in 2014, with less than 9% of the world's arable land feeding 22% of world's population, indicating a substantial contribution to global food security. However, compared with developed economies, such as USA and European Union (EU), more than half of the increased crop production in China can be attributed to a rapid increase in consumption of chemicals, particularly fertilizers. Excessive fertilization has caused low nutrient-use efficiency and high environmental costs in grain production. We analyzed the key requirements underpinning increased sustainability of crop production in China: (1) enhance nutrient use efficiency and reduce nutrient losses by "fertilizing roots not soil" to maximize root/rhizosphere efficiency with innovative root-zone nutrient management; (2) improve crop productivity and resource-use efficiency by matching the best agronomic management practices with crop improvement via breeding; and (3) promote technology transfer of the root-zone nutrient management to achieve the target of "high yields and high efficiency with low environmental risks" on a broad scale. Coordinating grain production and environmental protection through increasing the efficiency of nutrient use will be a key step in achieving sustainable crop production in Chinese agriculture.

Keywords: Chinese grain production; resource input; fertilizer; nutrient use efficiency; root zone nutrient management; root growth, environmental protection; food security

1. Introduction

There has been dramatic growth in world grain production over the last 50 years. From 1961 to 2014, global grain production of wheat, rice and maize increased 2.2, 2.5 and 3.9 times, respectively, which exceeded the rate of population growth (FAO, 2015). This has significantly decreased the proportion of malnourished people even as the earth's human population doubled to 9 billion (Godfray *et al.,* 2010). However, the challenges facing agricultural food production are greater than ever before because increased global food production must be achieved while improving efficiency of resource use and avoiding environmental degradation (Tilman, 1999; Tilman *et al.*, 2002; Shen *et al.,* 2013a, b; Zhang *et al.,* 2013; Chen *et al.,* 2014).

The doubling of agricultural food production worldwide up to the 1990s can be partly attributed to a 6.9-fold increase in N fertilization, a 3.5-fold increase in P fertilization, a 3.5-fold increase in the amount of irrigated cropland, and 1.1-fold increase in land under cultivation (Tilman, 1999; Tilman *et al.,* 2001). Because of pressure on environmental services and shortages of key resources, improved resource use efficiency rather than greater resource inputs must be a priority if we are to address another doubling in global food demand, which is projected for the coming 50 years (Cassman, 1999; Tilman *et al.,* 2002; Chen *et al.*, 2014).

Sustainable agricultural development must be compatible with the sound agronomic and environmentally-acceptable management with minimal environmental costs while we endeavor to meet an increasing food demand. It is a sobering fact that between 24% and 39% of maize-, rice- wheat- and soybean-growing areas in the world have not shown improved grain yield, or grain yields have stagnated or even collapsed, during the period 1961-2008 (Ray *et al.,* 2012). The situation is far worse in China with 79% of its rice cropping area, 56% of wheat and more than 50% of maize areas not showing an increase in yield from 1961 to 2008 (Ray *et al.,* 2012). However, China has fed its huge population (22% of the world) with 9% of the world's arable land, creating the "Miracle in China" during the past decades (Zhang *et al.*, 2012b, 2014). Total cereal grain production in China has been ranked the largest in the world in each of the last 20 years (Fig. 1B; FAO, 2015).

Food security is designated a top priority in the development strategy defined by the Chinese government, with a particular emphasis on the importance of increasing grain production (both quantity and quality) to meet the population's demand. The so-called "No.1 Document" released by the Central Government of China has focused on agriculture and food each year in 13 consecutive years since 2004. This strategy has greatly promoted resource use and technology advances to help deliver "self sufficiency in food" for the huge population in China, and even contribute food to other regions of the world.

China is still facing great challenges in delivering food security to its people. Compared with more than half a hectare of arable land per person in the United States, the average area of managed fields in China is only 0.1-0.3 ha/person (Yang, 2006; Chen *et al.*, 2011). Hence, the 'Miracle in China' was produced by hundreds of millions of farmers on very small parcels of land (Zhang *et al.*, 2013). No doubt, the scale of yield variation per unit area across the country is huge. For example, the average maize yield obtained by farmers in Northeast China, North China Plain and hill areas in the southern part of China were 5.3, 5.1 and 4.0 t ha^{-1}, whereas maize yields in experimental plots in these regions were 8.5, 7.3 and 6.7 t ha^{-1}, respectively, (Fan *et al.*, 2010). The highest attainable maize yields recorded in these regions, achieved through a high input of nutrients, water and labor, were 16.8 t ha^{-1} in northeast China, 18.0 t ha^{-1} on the North China Plain, and 14.7 t ha^{-1} in South China (Fan *et al.*, 2010). Such huge yield gaps between the actual and the potential yields were mainly attributed to constrains specific to a given area, but also to very large variation in management by numerous smallholders (Lobell *et al.*, 2009; Fan *et al.*, 2010, 2012; Shen *et al.*, 2013b).

An important issue that threatens China's sustainable grain production is inefficient use of resources (water and fertilizers) and the associated environmental pollution caused by excess fertilization. Chemical fertilizers have been driving China's grain production since introduction of the Borlaug's Green Revolution. In producing large amounts of food, China has consumed about one third of the global amount of chemical fertilizers (Zhang *et al.*, 2012b). There are several reasons for over-application of fertilizers in China: the farmers' traditional notion of "high fertilizer input, high yield output", combined with increased agricultural subsidies and income for farmers, easy access to chemical fertilizer in Chinese market due to high fertilizer production capacity and a relatively weak effect of increased chemical fertilizer use on crop production costs on small areas of land (Zhang *et al.,* 2010; Gao *et al.,* 2012; Kong *et al.*, 2014).

Excessive fertilization caused enormous nutrient imbalance in China's farmlands (Vitousek *et al.,* 2009; MacDonald *et al.,* 2011). In the North China Plain, the amount of N and P removed by grain was 361 and 39 kg ha^{-1}, respectively, while on average farmers applied 588 kg N ha^{-1} and 92 kg P ha^{-1} to croplands, leaving the astonishing yearly surpluses of 227 kg N and 53 kg P per ha in the 2000s (Vitousek *et al.,* 2009). Hence, most fields were maintained in a state of nutrient surplus due to excessive application of soluble inorganic nutrients to the soil. These surplus nutrients were uncoupled from plant demands spatially and temporally, exacerbating potential leakage out of the root zone (Drinkwater and Snapp, 2007; Shen *et al*., 2013a).

Surplus nutrients (defined as the difference between nutrient input and nutrient removal by plant harvesting) in farmlands have resulted in significant waste of resources. In global terms, China has contributed about 33% of N and 36% of P in nutrient surpluses (West *et al.,* 2014). This "high input, high output" production model in Chinese intensive agriculture is clearly unsustainable. Surplus nutrients in major China croplands have been creating serious environmental problems, such as air pollution, soil acidification and water eutrophication (Carpenter, 2008; Guo *et al.*, 2010; Childers *et al.*, 2011; Liu *et al.*, 2013). These challenging issues mean it is vital that China seeks novel approaches to managing its grain production and resource use in a sustainable manner.

China has now overtaken Japan as the world's second-largest economy, and as such, China will play an important role in world affairs in the next decades (Barboza, 2010). As one of its most important responsibilities, China must feed its large population by itself. China's demand for food will gradually increase with increasing population and economic development, and with changing diets as incomes increase and people wanting to consume more meat and dairy (Li *et al.,* 2013; Shen *et al.,* 2013b; Tilman and Clark, 2014). Hence, several extremely important questions need to be addressed: (1) can China produce adequate food to feed its large population with only 9% of the world's arable land, (2) can China sustain food production while reducing resource use and delivering other environmental services, and (3) what pathways should be taken to achieve sustainable grain production to overcome these challenges. Here, we summarize the historical trajectories of crop production and the cost of resources and environment in Chinese intensive agriculture within the global context, and assess potential approaches that may increase the sustainability of nutrient use and crop production in the next several decades.

2. Contribution of Chinese grain production to global food security

China contributed greatly to global food security during the past 50 years. China's grain production per capita doubled, from 209 kg per capita in 1949 to about 425 kg in 2011, allowing for a significant decrease in the proportion of undernourished people in the world (Godfray *et al.,* 2010; Zhang, 2011; Li *et al.,* 2013).

The Green Revolution has led to an unprecedented increase in agricultural production since the 1960s, which is largely a result of crop genetic improvement, enhanced soil fertility via chemical fertilization and irrigation, and control of pests and diseases by chemicals (Tilman, 1999; Khush, 2001). Grain production has increased in most regions of the world, including USA, EU and China (Fig. 1A). Grain production in USA increased steadily from 1961 to 1982, and thereafter it continued to increase but with evident fluctuations till 2014. In EU, grain production increased linearly from 1961 to 1997, and has stagnated since 1998. Unlike USA and EU, African grain production gradually increased from 1961 to 2014 (Fig. 1A). Chinese grain production has increased 4.0-fold over the last 50 years, from 110 Mt in 1961 to 557 Mt in 2014 (Fig. 1A). Chinese annual growth rate in grain production of 3.3% is higher than the world mean growth rate (2.3%) during the same period (FAO, 2015).

The grain production in China did not increase continuously during the last 50 years, but fluctuated (Fig. 1A). China’s grain production showed steady growth from 1961 to 1997, declined sharply from 1998 to 2002, and increased linearly during the last decade (2003-2014) (Fig. 1A). It was estimated that China was responsible for 12.5% of total global grain production in 1961 and up to 19.0% in 2014, whereas USA accounted for 18.7% of total global grain production in 1961, and only 15.8% in 2014 (Fig. 1B). The proportion of the global grain production was higher in China than USA after 1982. The EU proportion of the global grain production was only 13.7% on average over the last 50 years, showing a declining trend with time (14.7% in 1961 to 11.3% in 2014). In contrast, grain production in Africa accounted for less than 6% during the same time (Fig. 1B). Undoubtedly, the increased grain production in China has influenced the world food supply, with the problem of feeding China having global significance.

Since 1949, Chinese government has attached great importance to agricultural production. China grain production increased 4-fold from 1961 to 1997 (110 Mt to 458 Mt, Fig. 1). Many factors drove the dynamics of grain production. Agricultural inputs (chemical fertilizers, seeds, pesticides) were very limited around mid 20th century. Furthermore, grain production and land use were controlled by government to maximize grain production via integrating all available resources. Grain production could not meet domestic demand from 1961 to 1978 due to resource shortage and poor management, but the government-sanctioned integrative strategy has contributed significantly to alleviating the country’s famine (Figs. 1 and 5; Tong *et al.*, 2003). From 1961 to 1978, Chinese farmers applied organic manure to improve soil fertility, a situation not dissimilar to the response to resource shortage in African grain production (Yang, 2006; Tittonell *et al.*, 2007).

Breeding for semi-dwarf stature in wheat and rice increased grain yield potential in the 1960s (Evans, 1996). In maize, double-cross hybrids dominated (Li and Wang, 2010). In 1978, economic reforms opened China’s economy to the world and introduced the household responsibility systems that gradually replaced the commune system, permitting farmers more freedom in the management of land. This unleashed an untapped potential of the farmers, who were offered incentives to produce more grains (Fig. 1). From 1978 to 1997, grain production in China increased rapidly (Fig. 1; Li *et al.,* 2013). Crop yield (maize, rice and wheat) increased linearly. This situation greatly alleviated chronic food shortages and widespread malnutrition at the time (Tong *et al.,* 2003). Two factors could explain this increase: (i) benefiting from the Open Policy and household responsibility system, farmers in China started to buy agricultural materials, especially chemical fertilizers, to increase soil fertility and productivity, and (ii) in 1985, the Chinese government encouraged farmers to bring their surplus grain to market after they set aside grains for their family consumption and gave a fixed quota to the government as compulsory duty. From 1998 to 2002, grain production and crop yield declined sharply, because farmers' enthusiasm was hampered by the low grain price caused by the Asian financial crisis in 1998 (Fig. 1; Li *et al.*, 2013).

In contrast, in the 2003-2014 period China's grain production increased by 181 Mt, from 376 Mt to 557 Mt (Figs. 1 and 5). China has achieved a strong and continuous increase in annual grain production in 12 consecutive years. In such a period, Chinese government has paid much attention to agricultural production (Tso, 2004), abolishing the taxing of farm households and giving a range of subsidies to farmers (Huang *et al.,* 2011). These actions have caused a huge increase in wellbeing among farmers and increased the enthusiasm for farming. In addition, many farmers have voluntarily started to combine their own small and dispersed plots into larger plots that are suitable for mechanized management.

Most importantly, Chinese government has increased investment in agricultural science and technology. For example, to realize a grain yield increase of 30-50% nationally, the Chinese government has more than tripled its investment in agricultural research, from 7 billion RMB in 2000 to 24.4 billion RMB in 2009, with an emphasis on supporting the science that will boost yield while minimazing environmental consequences (Zhang *et al.,* 2013; Chen *et al.,* 2014).

Taken together, great contributions made by China to global food security were closely associated with a variety of factors, such as increasing resource inputs (fertilizers and other chemicals), suitable policies, effective government investment, and creation and application of advanced technology.

3. The resource and environmental costs in the contribution of Chinese grain production to global food security

The resource and environmental costs are one of challenges threatening China's future grain production (Figs. 2, 3 and 4). Achievements in grain production in China were highly dependent on intensive resource consumption, which came at serious environmental costs (Zhang *et al.*, 2010, 2012b; Shen *et al.*, 2013b; Chen *et al.*, 2014). To improve crop productivity, the irrigation area increased 3-fold (from 20.2 to 61.7 Mha from 1952 to 2011), agricultural machinery power nearly 5000 times (from 0.2 to 977 million kW) and electricity used in agriculture nearly 15,000 times (from 0.1 to 714 billion kWh) (Li *et al.*, 2013; Shen *et al.*, 2013b). However, the amount of yield increase with all these expanding inputs decreased, indicating that resource use efficiency declined in the last decades.

There was some expansion of area under cropping, for example by converting natural wetlands into artificial ones for grain production in Northeast Plain of China (Jiang *et al.*, 2009). It was estimated that 2 Mha of natural wetlands were converted to arable lands between 1979 and 2007, causing a large loss of biodiversity (Xing *et al.*, 2011). In wheat-maize rotation of North China Plain, excessive mining of groundwater aquifers for grain production has caused the water table to recede at a rate of around 1 m/year (from a few meters below soil surface in 1970s down to 30 m or more) (Wang *et al.*, 2002; Foster and Garduño, 2004). These issues highlight the importance of managing grain production and resource use in a sustainable way.

Chemical fertilizers, an important agricultural input, have boosted grain production during the past five decades. An increase in chemical fertilizer usage from 1 to 53 Mt over the last 50 years can partially explain a 4-fold increase in Chinese grain production (Fig. 2A) (Zhang *et al.*, 2012b). Chemical fertilizer consumption increased linearly with grain production from 1971 to 1990. From 1991 to 2011, the growth rate of chemical fertilizer consumption has surpassed that of grain production.

Compared with developed countries, over-fertilization on China's major cropland is common (Vitousek *et al.*, 2009; West *et al.*, 2014). In EU, chemical fertilizer consumption increased with grain production before 1980s, but since then fertilizer use started to decrease whereas grain production increased, suggesting an increase in nutrient use efficiency in grain production (Figs. 2B and 4B) (Zhang *et al.*, 2015). A similar trend was observed in USA (Fig. 2D). In the last decade, it was estimated that China was responsible for 19% of world grain production and 29% of chemical fertilizer use, while USA and EU have produced 16% and 12% of global grain with 12% and 8% of world chemical fertilizer consumption, respectively (calculated from Fig. 2). However, in Africa, the situation is different. Before 1980, the rate of increase in chemical fertilizer consumption was greater than that of grain production (Fig. 2C). Many factors such as poor soil quality, iandequate management, and water shortage contributed to poor crop fertilizer responses (Tittonell *et al.*, 2007). After the 1980s, grain production in Africa increased sharply together with an increase in chemical fertilizer consumption (akin to the situation in China in 1960s and 1970s), probably associated with improved soil fertility, increased seed quality and supply, and improved water supply (Denning *et al.*, 2009; Ejeta, 2010; Ttinsona, 2010).

The costs of adverse environmental consequences of Chinese agricultural production, e.g. in terms of agricultural greenhouse gas emissions, are also very high (Figs. 3A and 4A). Currently, agriculturally-related emissions based on chemical fertilizer application in China are two times higher than in USA or EU. In EU, emissions increased with grain production until an annual grain production of 250 Mt was reached in the 1990s, but they decreased with grain production thereafter. In USA, emissions steadily increased before grain production reached 300 Mt in the 1990s, and remained constant with increasing grain production thereafter. Agricultural emissions have continued to increase in Africa, although the intensity was quite low. However, in China, agricultural emissions based on fertilizer application have increased exponentially with grain production during the past 50 years (Fig. 3). For every ton of grain produced, 82 kg of chemical fertilizers were applied in China's croplands, which is more than three times as much as the amount of fertilizer in EU and USA during the last decade. At the same time, agricultural emissions per ton of grain produced in China were more than four times as high as those in EU and USA (Fig. 4).

Chinese society has undergone great changes during the past 50 years. GDP per capita exhibited exponential growth, from US$70 per head in 1961 to US$7590 per head in 2014 (Fig. 5). A huge amount of energy use has driven this dramatic increase in GDP. Similarly, high resource consumption and adverse environmental impacts are typical characteristics of China's grain production (Figs. 4 and 5). Innovations such as sustainable intensification, ecological intensification, and integrated agriculture that have been introduced in different parts of the world (Foley *et al.*, 2011; Tilman *et al.*, 2011; Conway, 2012; Grassini and Cassman, 2012) may be beneficial in China as well. However, China is a populous and large country, and there will be much debate over how to minimize the adverse environmental footprint of agriculture while feeding its enormous and increasing population. To address those challenges faced by China's food security, Chinese government advocated environmental sustainability as part of an "ecological civilization" (He *et al.*, 2013). The subsequent text discusses the relevant options and consequences.

4. Implications and perspectives

While huge demand for food and other agricultural products has been driven by population growth and the changing diets, it is paramount to increase resource use efficiency and environmental quality because of exacerbating resource shortages and environmental risks due to nutrient losses, land degradation, climate change, and other stressors. Chinese intensive agriculture must undergo sustainable intensification if the country is to simultaneously meet increasing food demand and a target of enhanced environmental sustainability (Godfray and Garnett, 2014). To achieve this target, one of the most important issues is to increase the sustainability of nutrient use in intensive agriculture. Three key approaches are needed if the country is to address these challenges (Fig. 6): (1) enhancing nutrient use efficiency and reducing nutrient losses by "fertilizing roots not soil" using innovative root-zone nutrient management;

(2) improving crop productivity and resource use efficiency by matching best management with crop improvement; and (3) promoting technology transfer of the root-zone nutrient management to achieve the target of “high yields and high efficiency with low environmental risk ” on a broad scale in China.

4.1 Enhancing nutrient use efficiency and reducing losses by “fertilizing roots not soil” using innovative root-zone nutrient management

Traditionally, Chinese farmers have increased nutrient concentrations in the soil solution using excessive application of fertilizers based on the assumption that “high input means high output”, but have neglected the capacity of crop roots to mobilize nutrients from soil pools by increasing exudation of carboxylates (e.g. citrate) and enzymes (e.g. acid phosphatases) into the rhizosphere (Zhang *et al.,* 2010; Shen *et al.,* 2013a). Over-application of fertilizers could be one of the main reasons that China’s grain production has not increased proportionally with an increase in chemical fertilizer consumption in the last decades (Figs. 2 and 6).

A range of recent studies have shown how crop yield can be maintained or even increased while fertilizer application is reduced; this was achieved by managing the nutrient supply in the root zone within an optimal range (Ju *et al.,* 2009; Zhang *et al.,* 2014, 2015). Such a strategy can (i) enhance biological potential of crops to efficiently mobilize and use soil nutrients, and (ii) optimize a match between the root-zone nutrient supply and the high-yielding crop nutrient demands, thus controlling nutrient losses to the environment (Zhang *et al.,* 2010, 2012a, 2012b; Shen *et al.,* 2013a). This can be beneficial in reducing the environmental footprint of fertilizer use (Zhang *et al.,* 2010; Chen *et al.,* 2011; Shen *et al.,* 2011, 2013a). Under conditions of high soil nutrient supply (particularly of N and P), root growth and exudation (eg. protons, carboxylates and/or acid phosphatases) are impaired (Shen *et al.,* 2013a; Teng *et al.,* 2013; Deng *et al.,* 2014). Therefore, the intensity and dynamics of nutrient supplies in the root zone (i.e. root-rhizosphere soil continuum) can regulate root growth and development as well as root physiological processes related to nutrient mobilization and uptake, and thus, to a large extent, determine nutrient use efficiency and the rate of nutrient losses from the plant-soil system (Shen *et al*., 2011, 2013a). For example, in field experiments across three types of soils, a significant correlation was found between soil nitrate concentration and maize root length at the silking stage (Shen *et al*., 2013a). In addition, localized application of P and ammonium improved maize growth and its nutrient uptake by stimulating root proliferation and rhizosphere acidification in the calcareous soils of North China (Fig. 6) (Jing *et al.,* 2010, 2012; Ma *et al*., 2013). Our recent studies showed that increased soil P availability induced by faba bean root exudation stimulated root growth and P uptake in intercropped maize (Zhang *et al*., 2016), suggesting a significant effect of optimized root interactions in the root zone on increased nutrient use efficiency in intercropping systems (Brooker *et al*., 2015; Zhang *et al*., 2016).

Controlling root-zone nutrient supply intensity is the key step in maximizing root/rhizosphere efficiency (i.e. enhanced nutrient acquisition per unit root length, increased soil exploration related to the root architecture, and nutrient mobilization by root exudation) rather than depending on high use of chemical fertilizers. This novel concept of “root-zone nutrient management” based on the knowledge of relevant plant-soil interactions is characterized by applying the relatively small amounts of chemical fertilizers (as starter fertilizer) to manipulate root growth and distribution as well as the rhizosphere processes. By applying this concept, for example, in North China Plain and Taihu region of East China, fertilizer usage was reduced by 30-60% without reducing yields of rice, maize and wheat in three consecutive years, while N losses were reduced by 50% (Ju *et al.,* 2009; Peng *et al.,* 2010; Cui *et al.,* 2014).

Enhanced growth could contribute to greater nutrient use efficiency from both native and applied nutrient (especially N) sources, because rapidly growing plants have larger root systems that more effectively exploit soil resources (Shen *et al.,* 2011, 2013a). Improved crop yields could increase N use efficiency and reduce greenhouse gas emissions at a given level of fertilization (Cui *et al*., 2014). In North China Plain, when initial soil NO_3–N content in the root zone (90-cm soil depth) was around 180 kg N ha^{-1} due to over-fertilization, maize grain yield was maximized at 8 t ha^{-1}. In contrast, maintaining initial soil NO_3–N content at 90 to 100 kg N ha^{-1} in the root zone was recommended for optimal nutrient management, producing 9 t ha^{-1} grain yield of maize (Cui *et al.*, 2013a, b).

Under field conditions, N overuse inhibits root growth at the early growth stage and fails to increase the final N uptake and grain yield (Peng *et al.*, 2012; Shen *et al.*, 2013a). Arbuscular mycorrhizal fungal (AMF) richness decreased when more N fertilizer was used (Wang *et al.*, 2015). Similarly, under the high soil P level in the root zone, root growth and root exudation capacity are greatly inhibited. It should be borne in mind that high soil P fertility has been built up in most of Chinese farmland due to overuse of P fertilizers in the past decades, resulting in trebling of the available P content (as Olsen-P with $NaHCO_3$ extraction method) in topsoil from 7.4 mg kg^{-1} in 1980 to 25 mg kg^{-1} in 2007 (Li *et al.*, 2011). Some root traits (i.e., root dry weight, root length density, arbuscular-mycorrhizae colonization, acid phosphatase activity, and expression of genes encoding phosphate transporters, phosphatases, ribonucleases and expansin) exhibited inducible responses to P deficiency, changing to inhibitory responses at or near the optimal P supply for maximum grain yield (Shen *et al.*, 2013a; Teng *et al.*, 2013; Deng *et al.*, 2014). Under field conditions, grain yield was highest at Olsen-P of 20-30 mg kg^{-1} for wheat (Teng *et al.*, 2013) and 5-10 mg kg^{-1} for maize (Deng *et al.*, 2014); at these critical levels, efficient P uptake by plant roots was maintained at minimized P application rates (Shen *et al.*, 2011, 2013; Teng *et al.*, 2013; Deng *et al.*, 2014). Thus, maintaining root-zone nutrient supply within an optimal range by optimizing fertilizer nutrient application, which can maximize root/rhizosphere efficiency, is critical for (i) improving nutrient use efficiency, and (ii) reducing a risk of potential environmental pollution (Fig. 6A) (Shen *et al.*, 2013a).

Besides plant root morphological and physiological responses to root-zone soil nutrient supply, microorganisms could also play a critical role in enhancing nutrient acquisition and efficient use by plant. For example, plants increased P acquisition and uptake through enlarging absorption area by mycorrhizal colonization or enhancing nutrient mobilization by mycorrhiza or phosphate-solubilizing bacteria (Fig. 6A). Arbuscular mycorrhizae colonization rate was kept high for efficient P acquisition at the critical root-zone P concentration (Teng *et al.*, 2013). In addition, the mineralization of soil phytate could be promoted by the interaction between mycorrhizal fungi and their hyphosphere phosphate-solubilizing bacteria (Zhang *et al.*, 2014). One of the mechanisms for soil phytate utilization was hyphosphere acidification induced by absorption of ammonium by the mycorrhizal mycelium leading to an increase in phosphatase activity, and consequently enhanced mineralization of organic phosphorus and improved maize uptake of P from phytin-P (Wang *et al.*, 2013).

Another successful example of root zone/rhizosphere management (using a P-banding approach) is the manipulation of root capacity to forage for locally-applied nutrients, which is an effective strategy for increasing root growth and P use efficiency in the intensive farming systems (Figs. 6A and 7). For example, localized application of optimal fertilizer combinations (phosphate plus ammonium) stimulated root proliferation and rhizosphere acidification in calcareous soils of North China, thus increasing use efficiency of N and P (Jing *et al.*, 2010, 2012; Ma *et al.*, 2013), as well as uptake of Zn and Fe (Ma *et al.*, 2014). The appropriate root-zone/rhizosphere nutrient management can increase yields by 8-27%, N and P use efficiency (kilograms of grain per kilogram of nutrient applied) by 40% and 200%, respectively, which effectively integrated the plant biological potential to enhance nutrient acquisition with nutrient management under field conditions. These case studies show an effective and novel approach of root/rhizosphere-based nutrient management for achieving high crop production, efficient nutrient use, and environmental protection (Figs. 6 and 7) (Zhang *et al.*, 2010; Shen *et al.*, 2013a; Cui *et al.*, 2014).

Our recent study on root management in North China suggested that 3-8% of total root length or root biomass being as deep as 30 cm could greatly enhance maize growth and yield under drought conditions, indicating a potential strategy to manipulate root growth and distribution. Integrated root management by deep ripping to facilitate deep root penetration as well as localized fertilization to enhance shallow lateral root proliferation can deliver sustainable maize production with reduced nutrient inputs (Figs. 6 and 7) (Wu, 2016; Shen *et al.*, 2013a). In Heilongjiang province, the root-zone/rhizosphere management significantly increased maize grain yield (by 14.4%) and the amount of grain produced per kg of N applied (by 31.4%) in

2011-2015 compared with the farmers' standard practice (Fig. 7). Based on our meta-analysis, yields of maize, rice and wheat can be improved by 10.3%, 8.2% and 10.2%, respectively, by adopting the root-zone/rhizosphere management to optimize soil nutrient supply intensity and incorporate new genotypes and other agronomic practices (Fig. 6).

The Chinese government has initiated a series of programs to promote transformation of China's grain production (Shen *et al.*, 2013b; Liu *et al.*, 2015). One of the most influential plans is "zero growth of fertilizer consumption", by which the annual increase in total fertilizer use is projected to be less than 1% from 2015 to 2019 (with no further increases from 2020) without yield penalty. Total funding of 800 million US dollars will be invested to support the implementation of the N Fertilizer's Zero Increase Action Plan in different regions and for various crops across China in the next five years (2015−2020) (Liu *et al*., 2015). This program encourages researchers, policy makers and farmers to increase fertilizer use efficiency and crop production as well as reduce the environmental risk by developing adaptive innovative technologies, improving policy and governance (such as cutting subsidies, regulating fertilizer price, controlling fertilizer application, and merging small parcels of land), and instituting effective knowledge transfer to promote the transformation of China's grain production from the intensive to sustainable farming systems (Figs. 6B and C).

4.2 Improving crop productivity and resource use efficiency by matching best nutrient management with crop improvement

Crop yields in developing countries have not kept pace with advances in agronomy (George, 2014). Achieving high crop yield hinges on integration of various resource inputs (water, fertilizer, seeds, etc.) and agronomic practices to optimize crop growth (Chen *et al.*, 2011; George, 2014). However, most farmers in China are not well educated, and they have other jobs near their hometowns (Zhang *et al.*, 2013), making agricultural income from the average Chinese farm a small proportion of total family income. Hence, most farmers do not intend to invest large amounts of time on their small plots (Shen *et al.*, 2013b; Zhang *et al.*, 2013). This situation represents a great challenge for China's agricultural scientists attempting to achieve high crop yield on a broad scale across different regions. Moreover, the major limitations to achieving high-yield crop production in China are also associated with (i) poor seed and soil quality, (ii) limited access to new technologies, and (iii) poor soil and crop management by farmers, such as poor sowing conditions, large variability in stand uniformity, and improper plant protection (Lobell *et al.,* 2009; Fan *et al.,* 2010; Shen *et al.,* 2013b).

The integrated soil–crop system approach, based on the root-zone nutrient management, was adopted with the aim of doubling maize yield relative to current farmers' practices; it achieved mean grain yields of 13.0 t ha^{-1} on the on-farm experimental plots with no increase in N fertilizer use (Chen *et al*., 2011). Further study showed that 1.3, 1.7 and 3.7 t ha^{-1} yield gaps in rice, wheat and maize, respectively, could be closed by improved nutrient management and agronomic practices (Chen *et al.,* 2014). It is estimated that if farmers in China could increase average grain yield to 80% of yields achieved by scientists in experimental plots by 2030, the food produced on the area the same size as that planted in 2012 would be sufficient to feed Chinese people (Chen *et al.,* 2014). Therefore, it is urgent to improve grain yield and reduce resource inputs with the best management practices based on the root-zone/rhizosphere principles (Fig. 6).

The yield potential in some of the world's most intensive cropping systems needs to be improved as a matter of urgency (Mueller *et al.,* 2012). As mentioned before, wheat yields in EU have stagnated during the last decade, although they increased sharply from 1961 to 2000. In China, rice yields have remained at about 6 t ha^{-1} since the 1990s. Maize yields in USA have not increased during the last decade (Ray *et al.,* 2012). It is difficult for farmers to maintain yield increases year on year when their average yield is about 80% of the yield potential (Cassman, 1999). Indeed, yields of rice in China, maize in USA and wheat in EU appear to be at or near 80% of their yield potential (Cassman *et al.,* 2003; Mueller *et al.,* 2012); hence, yield plateaus in those regions are likely caused by the average farm yields approaching a biophysical yield ceiling for the crop (Duvick and Cassman, 1999; Peng *et al.,* 1999).

Another important factor contributing to the yield stagnation is climate change and variability (Alston *et al.,* 2009; Lobell *et al.,* 2011; Lin and Huybers, 2012). Drought during stem elongation as well as heat stress during grain filling have affected wheat yields in temperate climates since 1990 (Brisson *et al.,* 2010). The effects of unfavorable climate change and variability on cereal yields in some countries in the last decades have been large enough to counteract a significant portion of the increases in average yields due to improved technology and other factors (Lobell *et al.,* 2011). International Rice Research Institute found direct evidence of decreased rice yields caused by increased night-time temperature. Rice yield declined by 10% for each 1°C increase in the growing-season night-time temperature in the dry season (Peng *et al.,* 2004). In Northeast China, climate change (decreased total precipitation and sunshine hours) led to a reduction in maize potential yield by an average of 13% across different hybrids; however, modern maize hybrids exhibited increased yield potential and resource use efficiency despite adverse climate changes (Chen *et al.,* 2013). The breeding programs should pay more attention to improved performance of their genotypes in the 'future' growth environmental conditions to address the challenges of global climate change and variability in the next-generation agriculture (Brisson *et al.,* 2010).

Crop varieties with high yield and high nutrient use efficiency are also urgently needed in intensive farming systems. As mentioned above, when farm yields reach about 80% of the yield potential, it is hard to ensure continuous yield gains through crop management. Thus, plant breeders need to continue developing novel crop cultivars with increasing yield potential. Additionally, in the past plant breeding has occurred under the management regimes with extravagant additions of nutrients and sufficient water (Boyer, 1982), which is going to be increasingly difficult to provide in the future. Thus, developing high-yielding crop cultivars with reducing nutrient and water inputs will be a significant challenge.

Root system architecture (RSA) is crucial to nutrient and water uptake in the soil profile. Immature RSA is primarily controlled by plant genetics. With time, RSA responses to variable environments are determined by a combination of genetic and environmental components (Rogers and Benfey, 2015). The hypothetical ideotype of RSA for efficient nutrient and water acquisition has been proposed (Lynch, 2013; Mi *et al.*, 2010). For example, shallow basal root growth angle and long root hairs can increase P uptake efficiency in common bean by enhancing topsoil exploration, given that P is relatively immobile in soils, and is often concentrated in the top soil (Miguel *et al.*, 2015). The 'steep, cheap, and deep' roots are thought to enhance the capture of soil water and N in maize by improving subsoil exploration (Lynch, 2013; Lynch and Wojciechowski, 2015), suggesting the possibility of breeding crops with potentially beneficial root traits. Under field conditions, maize root length density in the deep soil profile (30-150 cm) showed a significant positive correlation with nitrate depletion in the subsoil (60-90 cm) (Wiesler and Horst, 1994). Rapid development of roots foraging in deep soil layers would increase the capture of nitrate (Wiesler and Horst, 1994; Dunbabin *et al.*, 2003), and also avoid production of roots in the topsoil where drought may limit water and nutrient scavenging (Fig. 6) (Pennisi, 2008). In maize, deeper roots produced at low metabolic cost improved yield under drought (Lynch, 2015; Lynch and Wojciechowski, 2015). Plant roots growing in continuous biopores could also efficiently explore nutrients and water in deeper soil layers (more than 85% of wheat roots were found to be concentrated in those channels and biopores, Fig. 6A) (White and Kirkegaard, 2010; Wasson *et al.*, 2012).

Plant breeders are turning their attention to improving specific root traits to increase yields and achieve sustainable resource use in the target environments. By integrating the root and the above-ground traits using maize genetic populations, significant genetic relationships and major common QTL were determined among root traits, efficiency of N, P and water use, and yield (Azevedo *et al.*, 2015; Cai *et al.*, 2012; Landi *et al.*, 2010; Li *et al.*, 2015). Selection of QTL for RSA in maize could improve N use efficiency (Li *et al.*, 2015; Mu *et al.*, 2015) as well as drought tolerance (Landi *et al.*, 2010). By comparing root traits of maize grown in the field in China and the US, it was found that a large and deep root system, with an appropriate architecture and higher stress tolerance (to increased plan density, drought and N deficiency), was associated with high nitrogen use efficiency in maize production (Yu *et al.*, 2015).

Recent studies identified *DEEPER ROOTING 1* (*Dro1*) gene underlying a rice QTL for deeper roots; a near-isogenic line (NIL) (*Dro1* introduced into shallow rooting cultivar) had enhanced rooting depth, drought tolerance, N uptake, and grain yield (Arai-Sanoh *et al*., 2014; Uga *et al*., 2011, 2013). Another rice gene *PHOSPHORUS-STARVATION TOLERANCE 1* (*Pstol1*) encodes a crown-root-specific kinase controlling root growth at low P (Gamuyao *et al*., 2012), underlying the phosphorus uptake (*Pup1*) QTL; overexpression of *Pstol1* enhanced early root growth and significantly improved grain yield in low-P soil by enhancing acquisition of P and probably N and water (Gamuyao *et al*., 2012).

It is worth noting that the above two genes conferring low-nutrient and drought tolerance through enhanced root function originated from the exotic germplasm. Given the extensive natural genetic variation in root traits, genetic improvement of root system structure and function offers a real chance to produce cultivars for high-yielding, nutrient-efficient, and resilient agricultural systems.

4.3 Enhancing technology transfer to achieve "high crop yields and high nutrient use efficiency with low environmental risk" on a broad scale

Using new technology transfer infrastructure is the key point in translating the new technology into productivity in practice. In many farming systems around the world, farmers cannot obtain independent agricultural information due to a lack of appropriate extension services (Baulcombe *et al.*, 2009; Shen *et al*., 2013b; George, 2014). For example, many farmers do not know how to distinguish the genuine from fake fertilizers (Zhang *et al.*, 2013). For most farmers in China, the complicated plant-soil interactions underpinning crop production are traditionally regarded as a "black box" (Fig. 6B). In pursuit of high yield, they often take insurance measure by applying larger amounts of fertilizer nutrients to soil than the crop demand is, resulting in high resource and environmental costs (Zhang *et al.*, 2010; Shen *et al.*, 2013a; Withers *et al.*, 2014).

To improve transfer of new technology into agriculture in China, China

Agricultural University has established a novel model of knowledge transfer in 2009, i.e. Science and Technology Backyards (STB), situated in different ecological zones (Shen *et al.*, 2013b). STBs are the new technology transfer platforms located in vast China’s rural areas, jointly run by scientists, graduate students and local farmers, with the mission of agricultural science and technology innovation, demonstration, and training and development of farmers and graduate students. The approaches of STBs are well adapted to local Chinese farms with unbalanced development and different scales despite the similar conceptual principles as mentioned before (Shen *et al.*, 2013b). In the STBs, farmers are informed of new developments by large-scale training, information exchange in field schools, and working together with professors and graduate students, who live in the backyards (Shen *et al.*, 2013b). On the other hand, scientists can also learn the local knowledge from farmers to modify and adapt their advanced science and technology to the local environmental conditions (Shen *et al.*, 2013b). By using this approach, integrated high-yield technologies based on the root-zone/rhizosphere nutrient management principles were applied in the farmers’ field plots. Compared with single small households (farmers that were not part of STBs), grain yield in the demonstration areas (farmers that were part of STBs) can be increased by 12%-17% in a wheat-maize rotation system in Quzhou county (Zhang *et al.*, 2012a). Simultaneously, resource (fertilizer and water) use efficiency was improved and nutrient losses were reduced in the demonstration areas (Zhang *et al.*, 2013). The new model of transferring technology has been widely adopted by local governments, with average grain yield of 15 t ha^{-1} in a maize-wheat rotation of North China Plain (Shen *et al.*, 2013b; Zhang *et al.*, 2014).

The objective of Chinese agriculture is to simultaneously achieve high crop yields, high nutrient use efficiency, environmental protection and increased farmer income by adopting integrated innovative technologies to underpin synergistic effects among resource use, environmental effects and food production. The application and extension of high-yielding, high-efficiency technology based on the root-zone/rhizosphere management greatly reduced chemical fertilizer application while maintaining a relatively high grain yield on a regional scale (Zhang *et al.*, 2014).

It is suggested that the target of “produce more with less” can be realized through development and application of innovative agricultural technologies combined with high-yielding and efficient cultivars for resource use, not only in experimental plots, but more importantly on a large regional scale.

5. Conclusions

China’s grain production and fertilizer use have changed from the low-input, low-output to high-input, high-output farming, and recently to high-yield, high-efficiency farming systems. The important drivers of these changes are issues of resources, environment protection and food security, science and technology, farmer behavior, and policy. Modern agriculture in China and around the world is seeking sustainable intensification characterized by “less produces more”, and is confronting significant challenges due to increasing pressure to ensure food security while preserving resources and environment. We have proposed a novel model to address these challenges by improving the sustainability of nutrient use in intensive agriculture by using root-zone nutrient management to maximize root/rhizosphere efficiency based on accurate soil nutrient supply capacity in the root zone, optimal root responses, efficient genotypes, and appropriate soil management.

Agricultural complexity requires the development of innovative technologies adapted to local regions, and adopted by end users, which we achieved by establishing ‘science and technology backyards’ in local villages as a new way of technology transfer in China. There is no doubt that improving the sustainability of nutrient use while increasing crop productivity cannot solve all the problems faced by modern agriculture, and joint efforts of scientists, farmers, entrepreneurs, and policy makers are urgently needed to address the challenges of sustainable food production. China’s success in improving sustainable resource use and increasing grain production will enhance food security and decrease poverty and environmental footprint. Chinese agricultural development is likely to provide valuable experience to other developing countries that are facing or will soon face similar challenges.

Acknowledgements

This study was supported by the National Basic Research Program (973-2015CB150405), and National Natural Science Foundation of China (31330070, 31121062). ZR is supported by Australian Research Council (DP130104825 and DP160104434).

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Figure Captions:

Fig. 1 Grain production (A) and its relative contribution (%) to the global production (B) in different countries or regions from 1961 to 2014. Grain production represents the amount of total production of maize, wheat, rice, barley, buckwheat, millet, rye, sorghum and triticale. Data from FAOSTAT database (FAO, 2015).

Fig. 2 Relationship between chemical fertilizer consumption and grain production in different countries or regions (A: China, B: EU, C: Africa, D: USA) from 1961 to 2011. Data from FAO (2015) and IFA (2015).

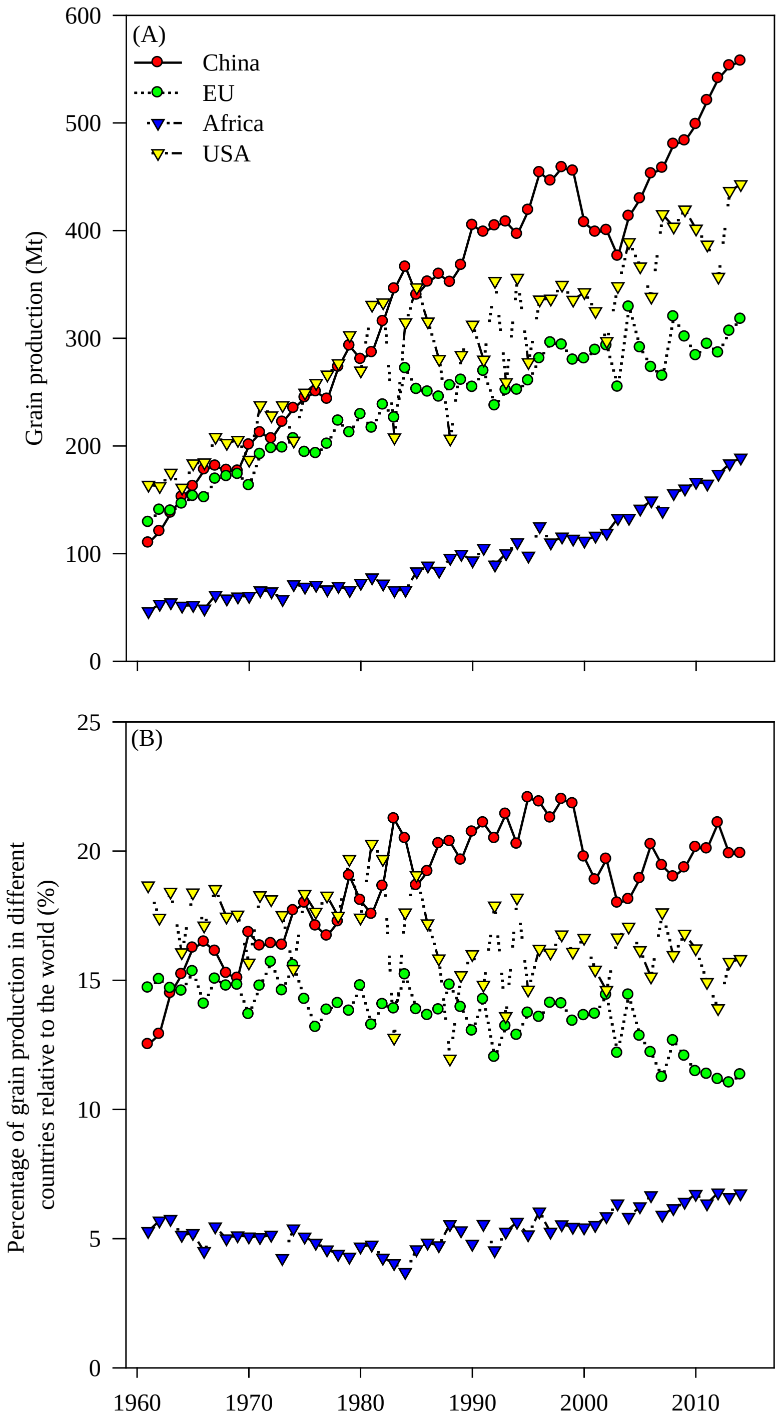
Fig. 3 Agricultural greenhouse gas emissions caused by grain production in different countries or regions (A: China, B: EU, C: Africa, D: USA) from 1961 to 2011. Data from FAO (2015) and IFA (2015). Agricultural emissions represent direct and indirect nitrous oxide (N_2O) emissions (expressed as CO_2 equivalent) from nitrogen (synthetic N fertilizers) added to agricultural soils by farmers. Specifically, N_2O is produced by microbial processes of nitrification and de-nitrification taking place at the site of addition (direct emissions), and after volatilization/re-deposition and leaching processes (indirect emissions). http://faostat3.fao.org/mes/methodology_list/E.

Fig. 4 Historical trends of grain yield, partial factor productivity (PFP) and agricultural greenhouse gas emissions (cf. Fig. 3) in different countries or regions (A: China, B: EU, C: Africa, D: USA) from 1961 to 2011. Data from FAO (2015) and IFA (2015). PFP was expressed as kg grain produced per kg chemical fertilizer applied.

Fig. 5 (A) The amount of resources (fertilizer, irrigation, plastic films and other chemicals) input into China’s major croplands to secure its grain production from a relatively constant land area. Data from National Bureau of Statistics of China, 1961-2015. Modified from Shen *et al.* (2013b). (B) The trajectories of GDP, energy use and CO_2 emissions per capita in China from 1961 to 2014. Data from World Bank (2015).

Fig. 6 Conceptual frameworks of root-zone/rhizosphere nutrient management for sustainable nutrient use in China’s grain production. (A) Root zone/rhizosphere management. AMF: arbuscular mycorrhizal fungi, PGPR: Plant Growth Promoting Rhizobacteria; (B) The old model of intensive farming with high input and high output, applying large amounts of fertilizers to soil; (C) The new sustainable farming model with high yield and high efficiency through appropriate root zone management (fertilizing roots to maximize root/rhizosphere efficiency). The thickness of the arrows in (B) and (C) indicates the relative size of the effects/processes.

Fig. 7 Maize growth performance with rhizosphere/root-zone nutrient management (RM) compared with farmers’ practice (FP). (A) Effects of RM on maize growth in comparison to FP; Compared with FP, the RM significantly increased maize grain yield by 14.4% and partial factor productivity (kg grain produced per kg N applied) by 31.4%, based on the average results during 2011-2015. (B) Machinery for planting seeds and locally applying starter fertilizer containing P and ammonium via deep banding; (C) Maize showing root proliferation in the location where the optimized nutrients were locally applied based on the rhizosphere/root-zone nutrient management (RM); (D) Local nutrient placement with different nutrient composition and supply intensity in root zone of maize; (E) Synergistic mechanisms of localized application of P plus ammonium showing increased root proliferation and NH_4-N-induced rhizosphere acidification in the banding area, resulting in enhanced P use and increased grain yield.



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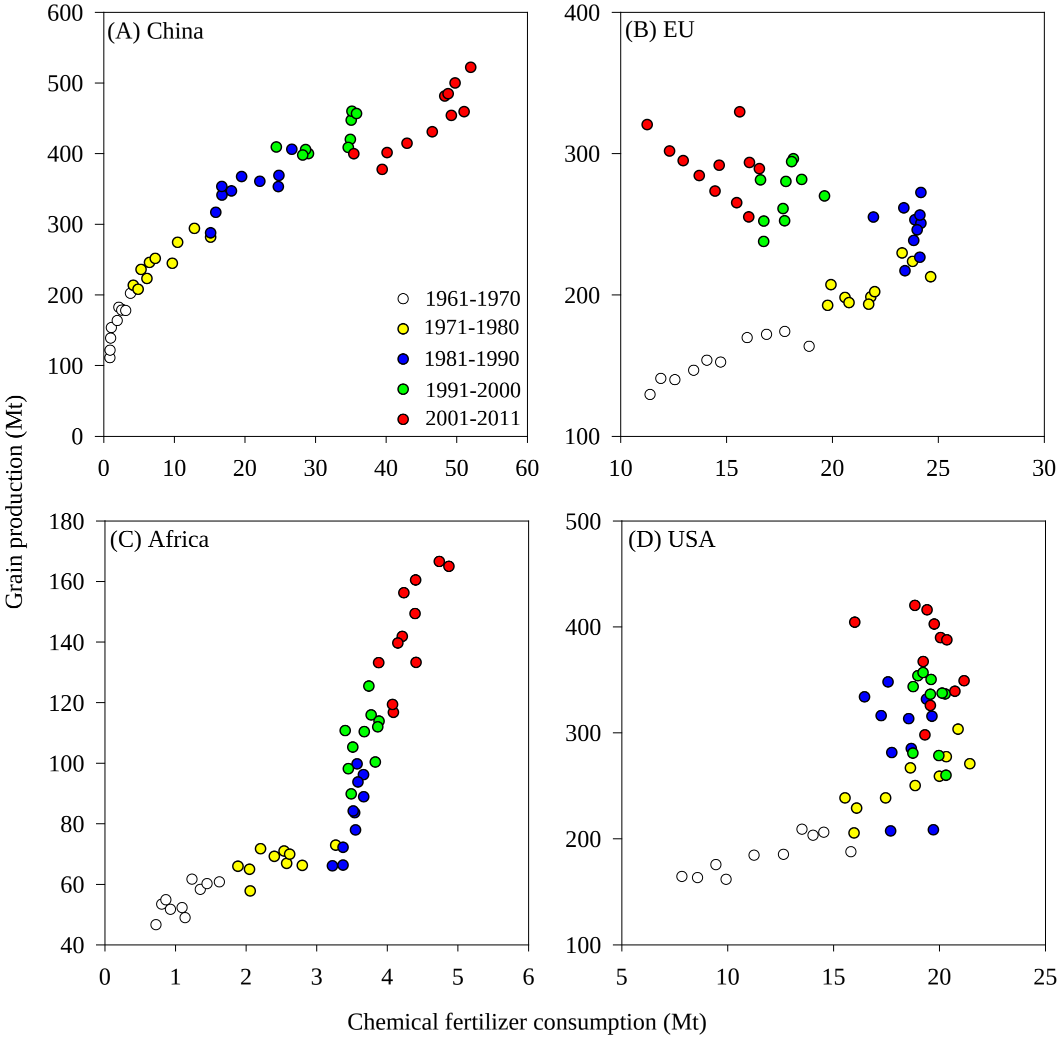

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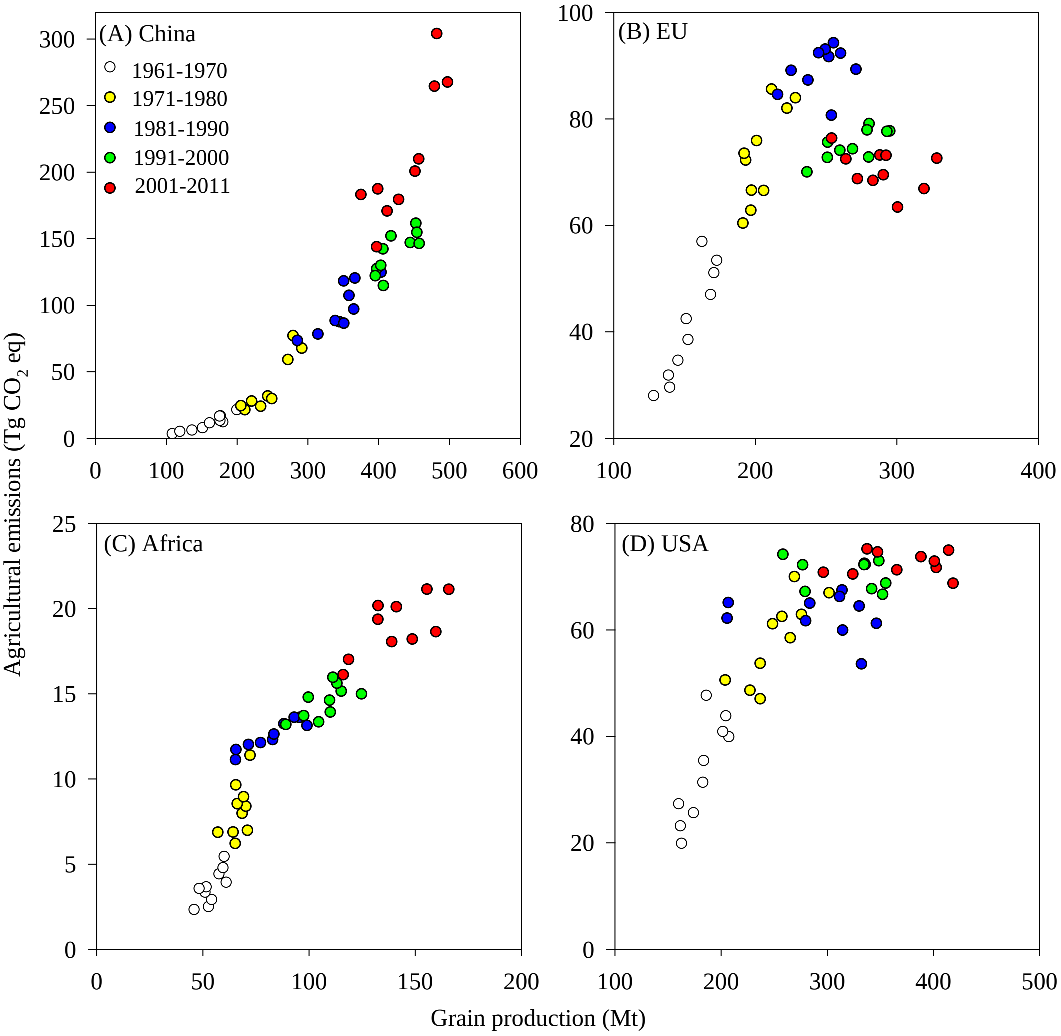

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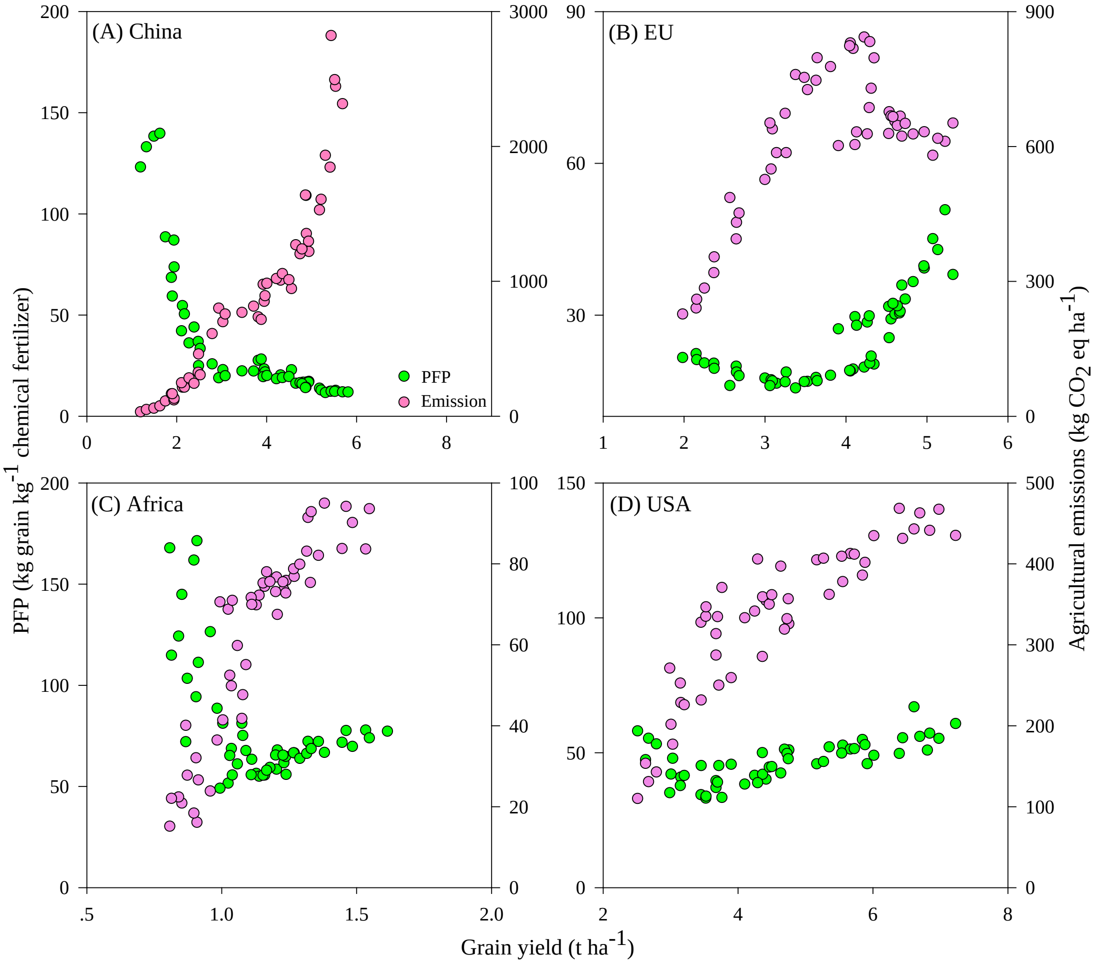

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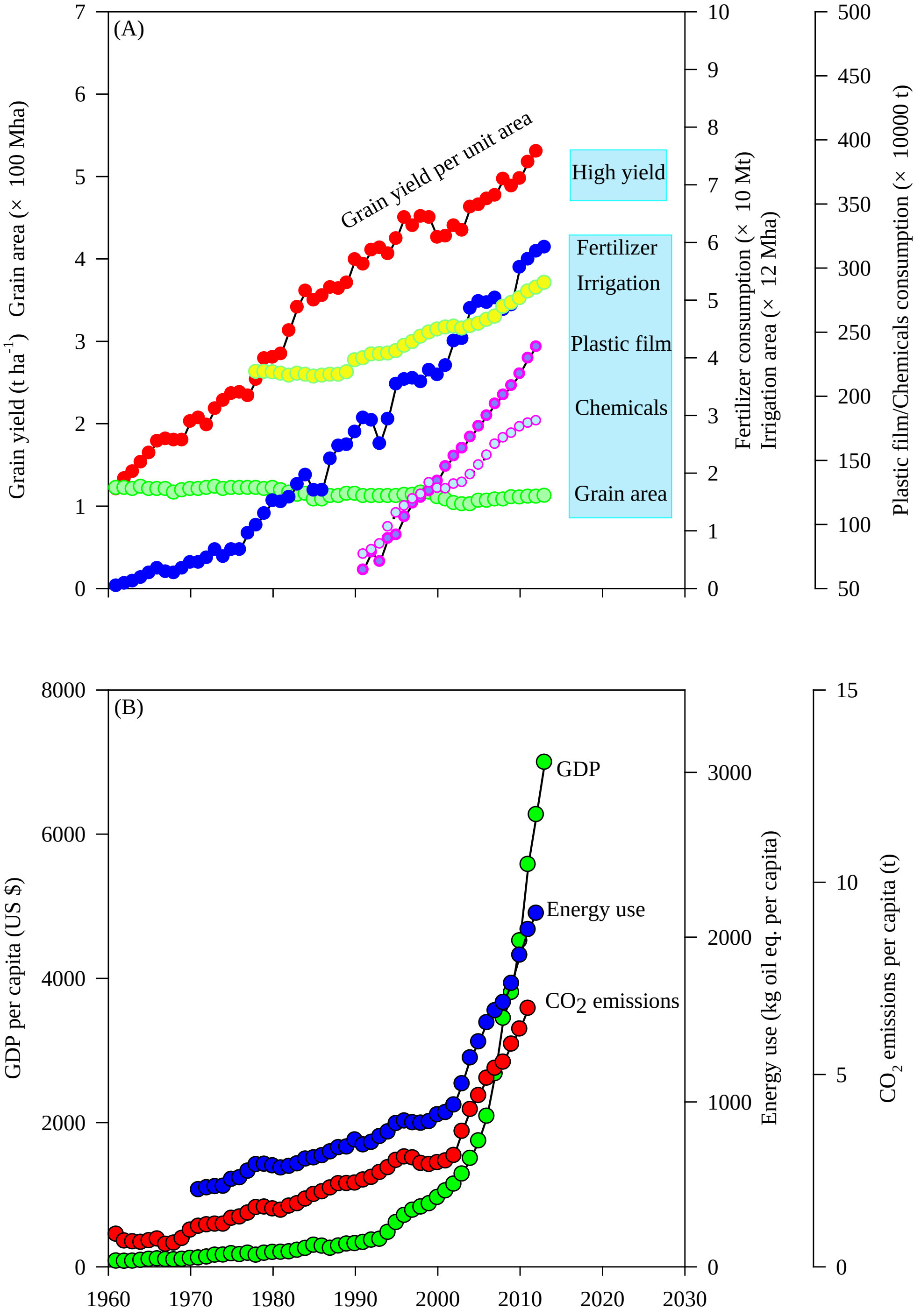

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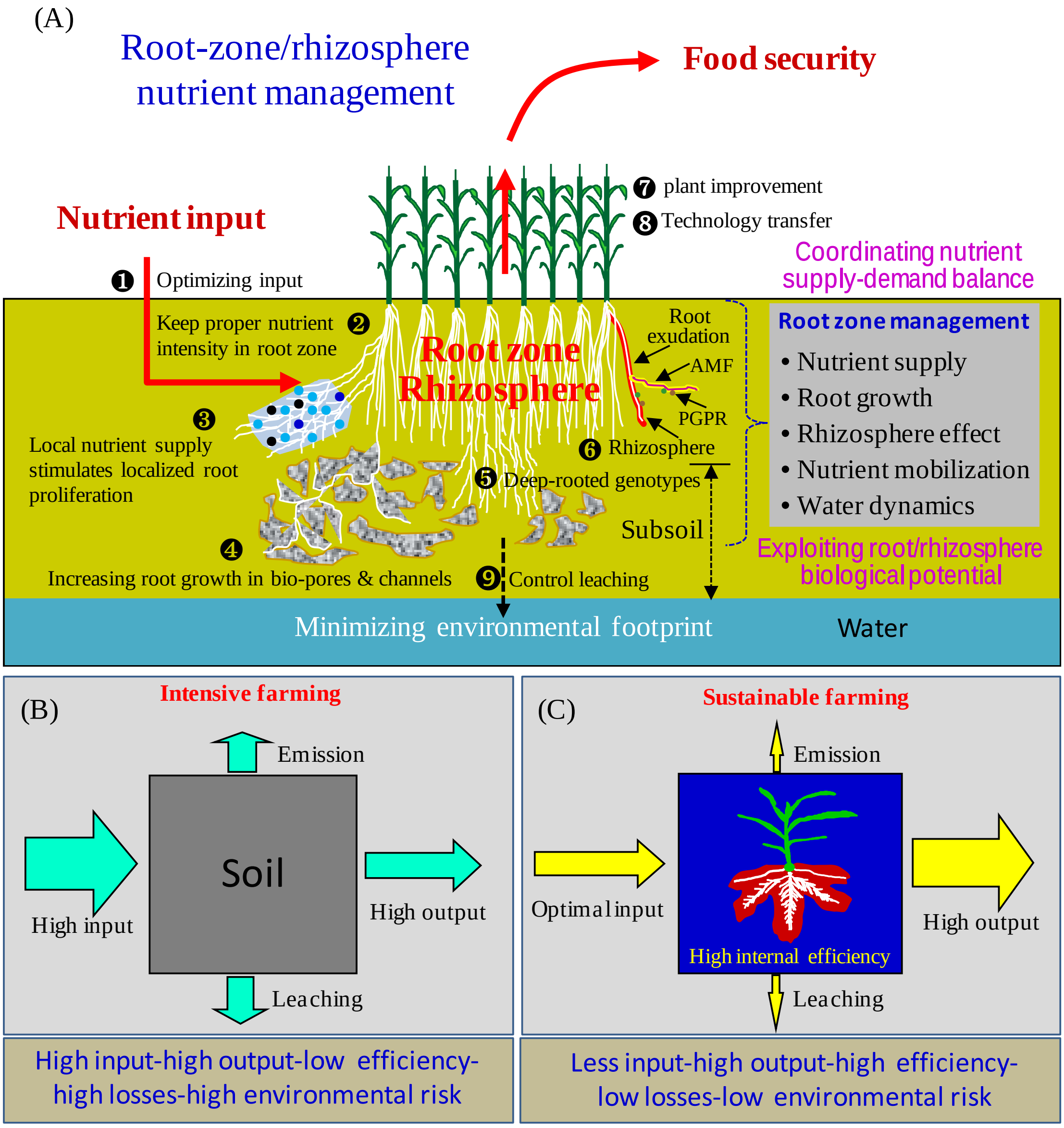

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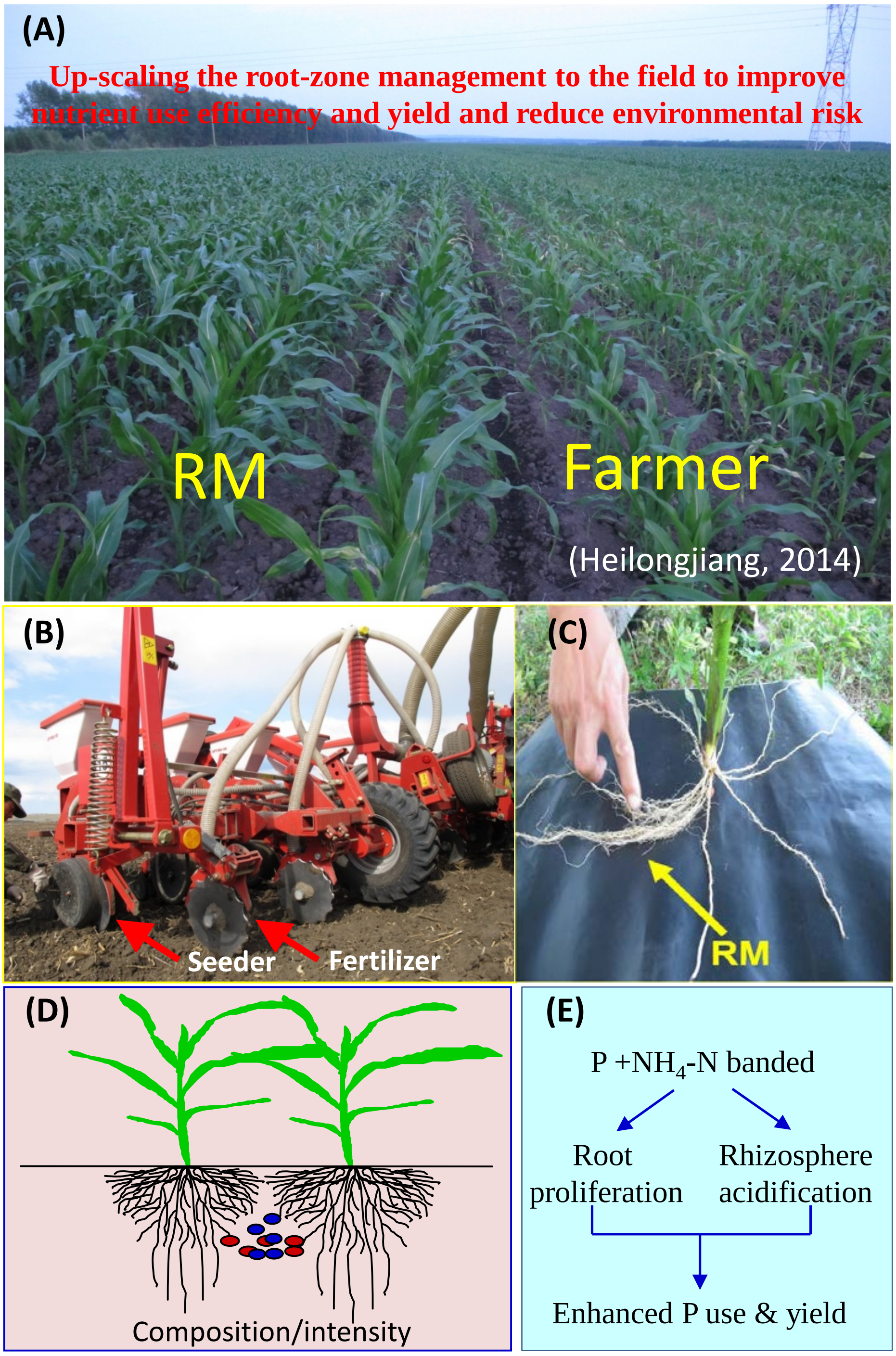

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