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An analysis of China's grain production: looking back and looking forward

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Chinese agriculture, food security, grain production, resource use, sustainable development.

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Abstract

Ensuring food security is the foundation of economic development and social stability. China is historically a country that is dominated by agriculture. In the past 60 years, China's total grain output increased by fivefold, from 113 million tons (MT) in 1949 to 571 MT in 2011, a statistic which provides inspiration to producers in other parts of the world. Grain production per capita doubled, from 209 to 425 kg during the same time period. At the national scale, China has succeeded in maintaining a basic self-sufficiency for grain for the past three decades. However, with the increasing population pressure and a growing appetite for animal products, China will need 776 MT grain by 2030 to feed its own people, a net increase of 35.9% from its best year on record. China's drive for future food security is challenged by problems such as low efficiency of resource use and resource limitation, diminishing return in yield response, competition for nonagricultural land uses, and environmental degradation. In this article, we analyze historical, temporal, and spatial variation in total grain production as well as the overall developing trends of current and future grain production, and discussed relevant options to overcome production constraints and further promote agricultural production.

Introduction

Producing enough food in a sustainable way to meet the growing global demand is one of the greatest challenges facing mankind in the 21st century. Accelerating trends in urbanization, environmental degradation, and climate change all hinder our ability to feed the world's growing human population projected to exceed nine billion by 2050 (Rosegrant and Cline 2003; Brown and Funk 2008; Lobell et al. 2008; Godfray et al. 2010). Regional imbalance in agricultural production is another constraint for supplying food to those who are most vulnerable and food insecure. While disadvantaged people in all countries may experience severe food insecurity, national-scale food security is

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currently not a concern in the developed economies of Europe, North America, and Oceania but a major problem in sub-Sahara Africa (Chen et al. 2011). There is a major concern about future food security in a number of regions, with the impacts of reduced food availability and access being felt first in those societies where people currently spend a high proportion of their income on food, such as Asia, sub-Saharan Africa, Latin America, and Caribbean region, and North Africa (Huang et al. 2002; Rosegrant and Cline 2003; Godfray et al. 2010).

China as the world's most populous nation has been sparing no efforts in pursuing national food security as a means of advancing economic development and maintaining social stability. From 1949 to 2011, China's total grain output increased fivefold from 113 to 571 million tons (MT) (Fig. 1), while per capita grain production grew from 209 to 424 kg/year (National Bureau of Statistics of China 2012). This marked achievement is largely attributed to expanding cereal production (rice, wheat, and maize) with the introduction of new varieties, intensification of cropping (double and sometimes triple cropping), and vastly increased inputs in irrigation, fertilizer, and other agricultural chemicals (Zhu and Chen 2002). However, environmental issues such as soil acidification, water contamination, N-deposition, and climate change associated with the overuse of fertilizers in grain production are escalating (Li et al. 2013). How China can sustainably grow its agriculture to meet the increasing demand in coming decades remains a hot debate. Compared to 2011, the population in China is predicted to increase from 1347 to 1462 million by 2030; more people will live in cities (an increase from 47.0% to 61.9%) (UN 2012), and annual per capita income will increase from 1833 to 16,000 USD (World Bank 2012). All these projected changes will push the country's grain demand to a higher level, beyond the current production output of 571 MT. For instance, meat consumption will continue to increase, pushing up the demand for feed grains in future. Meanwhile, low resource use efficiency in grain production, environmental degradation, and climate change can become serious constraints for China to sustain its economic growth and maintain the agricultural productivity in particular (e.g., Kang et al. 2008).

In recent years, world grain production has fallen short of consumption, and by the end of 2008, this drew world grain stocks down to their lowest level in the last few decades. Fortunately, China has maintained a grain self-sufficiency rate above 95%, contributing positively to global food security (Nie et al. 2010). In China, average consumption of cereals and three staple crops (wheat, maize, and rice) reached 207 and 255 MT, respectively, in the last decade, accounting for 22.5% and 24.9% of world consumption (FAO 2012a). If China imports more food, international grain prices will inevitably increase due to the limited grain supply capacity of the world market. This would exert negative impact on the food security in low-income food-deficit countries. Given its large population base and the sheer size of its economy, China's food security is not only a national priority but also a global matter. Therefore, ensuring sufficient food supply in China will help stabilize the world food market.

In this article, we first analyze the trends of grain production in China in the past six decades and identify relevant policies and influencing factors, and then we project the nation's grain demand for 2030 and examine major production constraints. Finally, we discuss potential

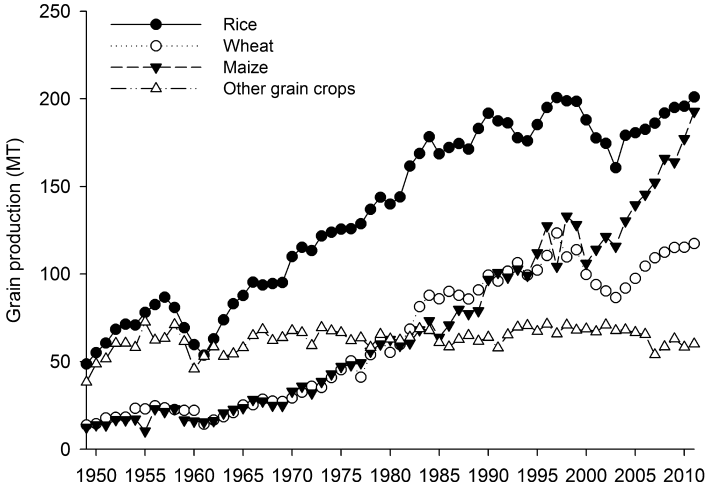

Figure 1. The evolvement of the output of rice, wheat, and maize over the period between 1949 and 2011. The data were collected from the China Statistical Yearbook published by National Bureau of Statistics of China in 2012. The other grain crops include millet, sorghum, legumes, and tuber crops.

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pathways for sustainable development of grain production in the future.

Grain Production Overview

Trends of total grain output

In FAO publications, grain refers to cereal grains only. However, in China (the National Bureau of Statistics) and here in this article, grain has a broader meaning, encompassing cereals, legumes, and tuber crops. From 1949 (the year the People's Republic of China was established) to 2011, China's annual grain output increased on average by 2.6%, from 113 to 571 MT. Of the total grain production, the three staple cereals (wheat, maize, and rice) accounted for 66.1% in 1949 (74.9 MT) but grew to 85.5% in 2011 (488.2 MT; Fig. 1). However, the increase in total grain production was not linear. It was slow and steady in the initial 30 years (a net increase of 200 MT from 1949 to 1978), rapid and dramatic for the next few years (a net increase of 100 MT from 1978 to 1984), slow and steady again for the subsequent 14 years (another net increase of 100 MT from 1984 to 1998). Thereafter, total grain output decreased considerably for several years, from 512 MT in 1998 to 431 MT in 2003. Fortunately, China's grain production has recovered its trend of upward growth since 2004, achieving another 100 MT increase between 2004 and 2011.

Many factors such as weather conditions, technological advancement, and policy changes interact to affect agricultural production. In China, government policies play a particularly critical and sometimes overriding role. For nearly 30 years after the "New China" was established (from 1949 to 1978), agricultural production was strictly state controlled via the commune system. Throughout the country, the grain market was under the total control of the state and grain price was determined exclusively by the government. Such rigid management controls hindered innovation and restricted agricultural development. Total grain output increased, owing to improved seeds, expanding irrigation, and increasing fertilizer input, but only at a limited pace. The year 1978 marked a turning point when land use reform was initiated. The commune system was replaced gradually with a household contracting mechanism, shifting land stewardship from collectively managed farms into individually chartered small plots, and the decision making on farmland management was transferred from commune leaders or government officials to the smallholder farmers themselves. This fundamental change provided farmers with the much needed incentive for enhancing production and improving life quality. The land use reform and open door policy greatly stimulated the enthusiasm of the farmers and their productivity. Combined with increases in agricultural production inputs and improvement in seeds as well as in management, total grain output increased rapidly. However, the Asian financial crisis in 1998 had a negative impact on China's agricultural production. Grain price dropped, pulling down farmers' income. The Government responded by adjusting the agricultural structure and reducing planting area of grain crops while increasing planting area of cash crops. Across the nation, planted acreage of grain crops decreased by 12.2% and reached the historically lowest point in 2003. From 1998 to 2003, total grain output decreased from 512 to 431 MT. Amid sharp criticisms and public concerns, in 2004 China aborted its long-standing policy of taxing farm households and instead began to provide farmers with four types of subsidy payments including "grain subsidy," "input subsidy," "quality seed subsidy," and "agricultural machinery subsidy" to encourage grain production (Huang et al. 2011a). The amount of subsidies for each farmer household was based on planted area for grain, so farmers were willing to expand the cultivated area in return for the subsidies. Between 2004 and 2011, the subsidy increased from 2.1 to 21.2 billion USD (Ministry of Finance of China 2012). Driven by the series of support policies, total grain output increased by 102 MT from 2003 (469 MT) to 2011 (571 MT). The planting acreage of grain crops climbed to 111 million hectares (Mha) by 2011, an increase of 11.2% from the historical low in 2003 (99.4 Mha).

The importance of three major grain production regions

There are three regions that are considered China's grain baskets, their collective contribution to the nation's total grain output increased steadily from 68.7% in 1978 to 72.3% in 2011 (Fig. 2). These regions are the mid- and lower Yangtze River region (Yangtze), the Northeast China Plain (NECP), and the North China Plain (NCP). The Yangtze region, covering seven provinces with >200 thousand square kilometers, has long been China's grain production center since Ming Dynasty. This region features a climate of northern subtropics, with annual average temperature of 14–18°C and precipitation around 1000–1400 mm. The planting system in this region is two crop harvests a year, even three in some areas. The abundant water supply and fine climate conditions favor rice and wheat production. There is a well-known Chinese saying, "When the area around Yangtze River has a good harvest, the entire country has enough food."

The other two regions, NECP and NCP, emerged as major grain production centers after the 1950s, as the results of government support polices and heightened investment in agricultural infrastructure. NECP, covering

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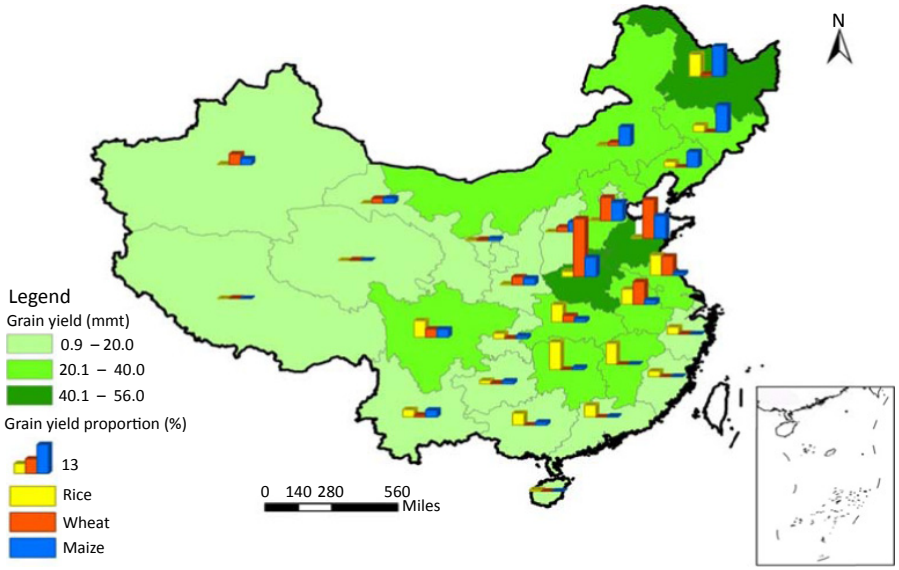

Figure 2. Map of three grain production regions in China. The map was formed based on the software of Global Information System (GIS), and the data were collected from the China Statistical Yearbook published by National Bureau of Statistics of China in 2012.

three provinces (Liaoning, Jilin, Heilongjiang) and 1.5 million square kilometers, is in the temperate and warm temperate zone and characterized by continental and monsoon climate types with an annual precipitation around 350–700 mm. The soil is fertile and the planting system is one crop-harvest a year, with wheat, corn, soybean, and rice being the major crops. Moreover, the region is rich in surface and groundwater and much of the rice area is equipped with irrigation. The NCP is located in the lower reaches of the Yellow River, covering six provinces with 310,000 km^2. This region has a typical temperate and monsoonal climate with four distinct seasons. Average annual temperature is about 8–15°C and precipitation is 500–1000 mm. The cropping system features three harvests every 2 years, mostly with a wheat–maize rotation.

Collectively, the three regions constitute a total of 75.0 Mha of arable land, accounting for 61.6% of the total arable land in the country (National Bureau of Statistics of China 2012). In 2011, cultivated area of grain crops in the three regions accounted for 76.4% of the total cultivated area in China. From 1978 to 1984, total grain output increased by about 103 MT (from 304 to 407 MT) in the country; 65.1% of the increase was in the three grain basket regions (from 209.4 to 276.2 MT) (Fig. 3). In the period between 1984 and 1998, another 100 MT net increase was achieved in the country, of which 70.9% was attributed to increases in the three regions. During the most recent push for grain production (2004–2011; 100 MT net increase), 90.6% of the increase was from the three regions. Clearly, the importance of the three grain baskets in China's food security

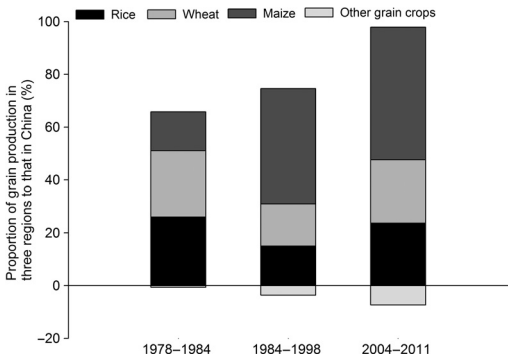

Figure 3. The proportion of the increased grain production in three regions to that in whole country.

has become progressively more critical in the past three decades. However, with the rapid development of intensive grain production in these three regions, environmental problems, such as eutrophication, soil acidification, N-deposition, and climate change associated with uses of fertilizers, pesticides, and agricultural machines have also intensified and may become serious constraints to future growth. Hence, it is important to evaluate whether further significant increases in productivity can be achieved in these already productive areas.

Meanwhile, the production of the three staple crops in the three regions also grew in both absolute terms and as a relative proportion of national production. Net increase in the three staple grains amounted to 67.5 MT from 1978 to 1984, accounting for 76.4% of the relevant increase in the country. Maize was the fastest-growing

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crop during this period in the country as well as in the three regions, accounting for 61.4% and 50.3% of the net increase in grain production in the whole country and the three regions, respectively. Moreover, maize production in the three regions accounts for 75.7% of maize produced in the whole country. Maize is the major feed crop for animal production and its rapid growth in popularity with farmers reflected the fast increasing demand from the population for more meat in their diet. Between 2004 and 2011, total meat production increased by 20.4% (from 66.1 to 79.6 MT). China's growing economy, income, and urbanization will further stimulate the appetite for animal products and thus additional demand for maize is inevitable. It is well known that a diet with a high content of animal protein is highly demanding of agricultural inputs, compared to the production of a largely vegetarian diet. Jagerskog and Clausen (2012) have shown that a very high proportion of the substantial use of water in Chinese agriculture since 1980 has been focused on extra meat production. Moreover, with the rapid development of the Concentrated Animal Feeding Operations (CAFOs), the growing disconnection between animal production in CAFOs and grain production is not conducive for the development of circular agriculture, for instance, it will be costly and impractical to bring manures from distant livestock farms to cropland where manure nutrients can be effectively utilized.

In the most recent push for grain production across the country (2004 and 2011), 90.7% of the national increase in the three staple grains was attributed to that in the three regions. Undoubtedly, China's food security depends heavily on the production output in the Yangtze, NECP, and NCP regions.

Grain production attributed to yield versus planting area

Total grain output depends on two factors: cultivated area and crop yield. From 1978 to 2011, total cultivated area for grain decreased from 121 to 111 Mha across the country, but total grain output increased from 305 to 571 MT owing to enhancement in yields. Rice yield increased from 4.1 t ha^{-1} in 1978 to 6.7 t ha^{-1} in 2011, wheat from 2.0 to 4.8 t ha^{-1}, and maize from 2.3 to 5.7 t ha^{-1}. Taken together, average grain yield increased from 2.5 to 5.2 t ha^{-1} during the 33-year time span.

Examined more closely, from 1978 to 1984, the 100-MT increase in grain output was attributed entirely to yield improvement (from 2.5 to 3.6 t ha^{-1}) whereas the acreage of grain crops actually decreased (from 120.6 to 112.9 Mha), so the yield improvement contributed 127% to the net increase in grain production in this period. Between 1984 and 1998, another 100-MT net increase in grain output was achieved, again mainly attributed to yield increase (by 0.8 t ha^{-1}, contributed 96% to the net increase in grain production) rather than planting area expansion (by 0.9 Mha only, contributed 3% to the increase in grain production). However, the situation changed during the period between 2004 and 2011, when the 100-MT increase in grain output was largely derived from an expansion of cultivated area, with a net increase of 9 Mha, which contributed 54% to the net increase in grain production, whereas crop yield only increased by 0.5 t ha^{-1}, contributed 41% (Fig. 4A). The substantial slowdown in yield improvement over the past three decades is a reflection of diminishing return as the increasing production inputs are met with a decreasing yield response. This slowdown also implies that there is a growing challenge in keeping up with the country's escalating grain demand. High use of fertilizer and water and decreasing yield responses, combined with shortages and escalating costs of these and other inputs, threatens sustained crop productivity for the future as well as the maintenance of a low environmental footprint in agriculture (Fan et al. 2011).

The trends at the national scale described above were also mirrored in the three basket regions, that is, increases in total grain output were dominated by yield improvement at first, and planting acreage expansion became increasingly more important recently (Fig. 4B–D). In fact, there was a net increase in the acreage of the three staple crops, totaling 11.5 Mha (from 50.8 to 62.3 Mha) between 2004 and 2011 in the three regions, which offset an actual decrease in grain acreage in other part of the country. As mentioned earlier, nationally the acreage increased by 9 Mha for the same time period. The expansion in the three regions was made up as follows: rice (2.5 Mha), wheat (2.8 Mha), and maize (6.2 Mha). Such planting area expansion for grain production resulted directly from decreases in the acreages of nongrain crops (oil crops, cottons, and hemp crops) as well as conversion of wetland in NECP into crop production (discussed later). These shifts reflected the fact that farmers were increasingly motivated in their engagement in grain production because of stable prices for grain crops, a hefty subsidy on grain production, and the development of labor-saving machineries. Once again, strong policies played a critical role in stimulating grain production allowing production to keep up with the growing food demand since 2004.

Food Security Challenges in Coming Decades

Grain demand by 2030

Human population in China is projected to peak at 1467 million in 2030. Per capita income is projected to reach

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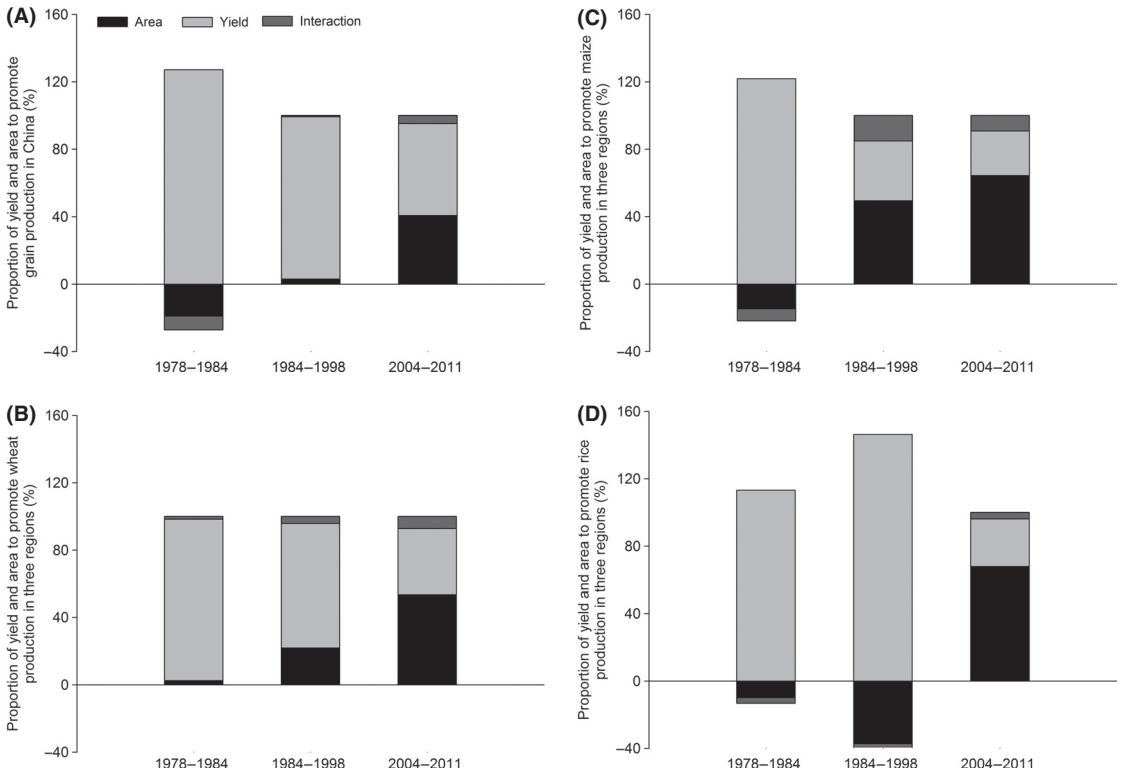

Figure 4. The contribution ratios of the crop yield and cultivated area to promote the grain production in China (A) and wheat (B), maize (C), and rice (D) production in three regions.

16,000 USD in 2030, a sixfold increase from 2011. Also, 61.8% of Chinese people will live in cities by 2030. All these changes have and will continue to bring significant increase in food demand (Heilig 1997). As shown in Table 1, food consumption in China increased dramatically from 1961 to 2007, especially for animal products such as meat and milk increased annually by 5.9% and 5.4%. In comparison, per capita consumption of cereal and egg in China exceeds that in USA, EU, and Japan; meat consumption is slightly higher than that in Japan but much less than that in the USA and EU (Table 1). One very clear contrast between China's diet and that of the other countries in comparison is the amount of milk consumption. In 2007, USA had nearly nine times, EU eight times, and Japan three times of China's per capita milk consumption.

Rapidly rising income in China fuels a growing appetite for animal products, which in turn pushes the grain demand even further. It takes roughly 7, 3, 2.1, 3.5, 2.5, and 2.1 kg grain, respectively, to produce 1 kg of beef, mutton, poultry, pork, egg, and milk (Liu, 2002). We calculated the quantity of grain needed for 2030 under a number of scenarios (Table 1). If the average Chinese dietary composition approaches that of Japan (2007 level), China would need 722 MT grain by 2030. Assuming that the country adopts the EU or USA diet, China would need 1445 or 1733 MT grain (Table 1). We also calculated grain demand based on the dietary recommendation of the Chinese Society for Nutrition (Table 1), and the corresponding grain demand would be 776 MT. This would be 204.4 MT greater than the country's best record of 571 MT (in 2011). In other words, to fuel an aspirational "Western diet," China will need to increase its total grain output by 35.8% from its record level in order to maintain grain self-sufficiency by 2030. Whether China will be able to attain this goal depends on many factors, not least the type of diet that becomes typical for the average Chinese. The health impacts of changes in diet need to be an important consideration for policy makers (Tansey 2013) but detailed discussion of these factors is beyond the scope of this article. However, some major constraints on future production are discussed below.

Constraints to crop yield

Assuming average crop yield remains the same as 5.2 t ha^{-1} in 2011, cultivated area would have to increase to 150 Mha, an increase of 36.4%, to meet grain demand of 776 MT by 2030 based on the per capita food intake recommended by Chinese Society for Nutrition. This is

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Table 1. The tendency of per capita food intake and prediction in 2030.

Year	Population[1] (million)	Per capita food intake[2] (kg/year)				Total grain (MT)
		Cereal	Meat[3]	Egg[3]	Milk[3]	
1961	667	93	3.7	2.1	2.5	81
1978	957	152	11.3	2.5	3.1	199
1984	1040	182	17.5	3.9	4.2	275
1996	1226	174	38.3	14.8	8.2	426
2004	1300	157	51.0	16.5	16.7	515
2007	1321	153	52.0	17.4	28.7	545
2030[4]	1467	112	122.1	14.3	253.8	1733
2030[5]	1467	125	83.4	12.4	241.4	1445
2030[6]	1467	115	45.9	19.6	76.5	722
2030[7]	1467	146	27.4	18.3	109.5	776

[1]The data of Chinese population in 2030 is based on the prediction of United Nations under the condition of the high birth rate (UN, 2012).
[2]The data of the per capita food intake are cited from Food and Agricultural Organization (FAO 2012b).
[3]The total consumption of the per capita food in terms of the grain is recalculated based on the different conversion rates of meats, eggs, and milk: 1 kg beef = 7 kg grain; 1 kg mutton = 3 kg grain; 1 kg poultry = 2.1 kg grain; 1 kg pork = 3.5 kg grain; 1 kg egg = 2.5 kg grain; 1 kg milk = 2.1 kg grain (Liu, 2002).
[4]Scenario 1 is calculated based on the per capita food intake of USA in 2007.
[5]Scenario 2 is calculated based on the per capita food intake of EU in 2007.
[6]Scenario 3 is calculated based on the per capita food intake of Japan in 2007.
[7]Scenario 4 is calculated based on the per capita food intake recommended by Chinese Society for Nutrition.

unlikely considering the ever-growing competition for land from nonagricultural sectors and potentially from biofuels. In fact, cultivated area decreased from 120.6 to 110.6 Mha in the past three decades, an average annual decrease rate of 0.3%. The central government has decreed that for the future, cultivated area for grain should be maintained at around 110 Mha (2011 level). Assuming this to be the case for the coming decades, crop yield will need to reach 7.0 t ha^{-1} in order to produce 776 MT grains by 2030. In other words, China must increase the unit grain yield per hectare by 34.6% from its best record by 2030 in order to keep up with the demand for grain nationally. In the last two decades, the crop yield increased from 4.1 to 5.2 t ha^{-1}, with an annual growth rate of 1.2%. If China can maintain the same growth rate of 1.2% in the next 20 years, by 2030 the crop yield would reach 6.5 t ha^{-1}, still short of the 7.0 t ha^{-1} needed for the 776 MT target.

Modern genetic and crop improvement programs designed to enable the capture of more carbon are now focused on substantially improving the yields of the world's major crops (Parry et al. 2011). Grain yield will be improved through improved photosynthetic efficiency, altered canopy and root architecture, modified seed development, and enhanced nutrient utilization efficiency. This will be introduced utilizing breeding, exploiting novel germplasm, transgenesis, and other forms of genome remodeling.

During the past six decades, improvement of crop yield was largely depending on resource inputs. From 1952 to 2011, irrigated area increased twofolds (from 20.2 to 61.7 Mha), annual consumption of chemical fertilizers 712 times (from 0.08 to 57 MT), agricultural machinery power 4886 times (from 0.2 to 977.3 million kW), and agricultural use of electricity 14,279 times (from 0.1 to 714 billion kWh). Meanwhile, the growing inputs of resources were accompanied by a diminishing response in grain yield (Fig. 5). For example, during the period between 1960s and 1990s, the partial contribution of chemical fertilizer to the yield increases in wheat, maize, and rice was by 40–60% (Lin and Li 1989), but for the period of 2000–2008, the contribution ratio dropped to 30.5%, 25.3%, and 18.7%, respectively (Zhang et al. 2008). Furthermore, many yield-enhancing technologies are already widely adopted, such as fertilizers, modern crop varieties, irrigation, and agricultural machinery, but the contribution ratio to total grain production by crop yield continues to decline. It is questionable if greater technological and resource inputs would lead to further greater production, and if so, at what price.

Constraints in the three grain basket regions

The three food basket regions produced 91.8% of the net increase in grain output in the whole country during the period of 2004–2011. Without doubt, China's pursuit of food security will continue to rely on these regions. However, there are serious constraints within these regions that hinder agricultural development in the future, for example, destruction of the wetland (Jiang et al. 2009)

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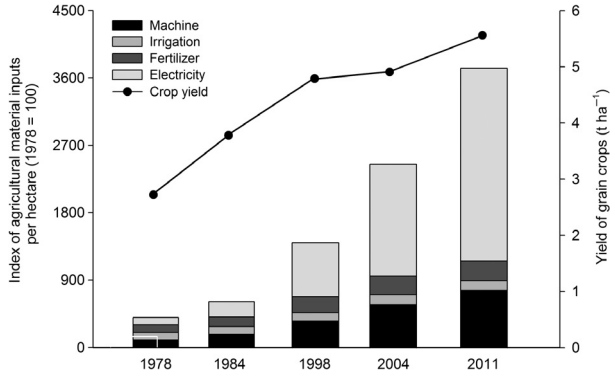

Figure 5. Increasing resource inputs for total grain production growth by 100 MT. The data were collected from the China Statistical Yearbook published by National Bureau of Statistics of China in 2012. The amount of agricultural material inputs in different years is showed by the index (1978 = 100). The nodes on the line represent the total yield of the maize, rice, and wheat in 1978, 1984, 1996, 2004, and 2011, respectively.

and soil erosion problems in NECP (Wang et al. 2008a, b), severe water shortage in NCP (Khan et al. 2009), and land competition in the Yangtze region (Chen 2007).

The NECP is China's most concentrated area of wetland, totaling 6.4 Mha in 2010 (Xing et al. 2011). Wetland, with important ecological functions and values, is an ecological landscape rich in biodiversity and one of the most important natural habitats for all walks of live. Unfortunately, exploiting the natural wetland for grain production has been on-going for decades in this region. An estimated 2 Mha natural wetland was converted into artificial wetland for grain production between 1979 and 2007, while the fastest growth of the artificial wetland occurred during the period between 2001 and 2007 (increased by 1 Mha) (Xing et al. 2011). This trend must be reversed because it is destructive, unsustainable, and potentially disastrous for the ecological system. In fact, in recent years, government has begun to implement a policy of conversion of farmland back into wetland.

Soil erosion is another widespread problem in NECP. This region's vast agricultural wealth resides largely in its 11 Mha of black soil, of which 8.2 Mha has been used for grain production. Black soil erosion has worsened in recent years. A consulting project of the Chinese Academy of Engineering estimated that the black soil layer is eroding at an annual rate of nearly 1 cm, with the annual erosion volume totaling 100–200 million m^3. Soil erosion takes away nutrients; and the reduction in total grain production caused by decreased soil fertility was estimated to be 2–4 MT annually (Wang et al. 2008a,b). Although various measures have been taken, for example, planting trees, establishing windbreaks, to prevent soil erosion, the current tillage practice is the main factor for soil erosion. Continuous corn or rice production in the NECP, as rotation with soybeans has disappeared, will eventually become a problem for soil quality (carbon removal due to harvesting stover) and pest management. The challenge is to protect the regions' natural resources, notably wetland and black soil, while sustaining or even increasing grain yields.

For the NCP, water scarcity is the most serious problem. Summer maize typically consumes 420 mm water and winter wheat 450 mm (Liu et al. 2002) but annual precipitation averages merely 500 mm and varies from 300 to 1000 mm (Li et al. 2005; Meng et al. 2012). Only 20–30% of the precipitation occurs during the winter wheat growing season (Wang et al. 2008a,b; Sun et al. 2010), therefore, the crop relies heavily on irrigation, typically 3–4 times per season (consuming 750–900 m^3 water per ha with each irrigation). Hebei province, one of the provinces in NCP, has 72.8% arable land with irrigation facility in 2011 (National Bureau of Statistics of China 2012). Agricultural water use accounts for 64.7% of total water consumption in NCP, and 70% of the agricultural water is derived from groundwater (through well construction with government subsidies) (Zhang et al. 2011). Excessive mining of groundwater aquifers in North China has caused the water table to recede, from a few meters below the soil surface in 1970s to 30 m or more, at a speed of around 1 m/year (Wang et al. 2002; Kang et al. 2008). Assuming the water use efficiencies of 1.5 and 2.7 kg t^{-1} for wheat and maize as in the optimized experiment in NCP (Meng et al. 2012), production of the required wheat and maize output in the region for 2030 (91.7 and 96.8 MT) would need 96.9 billion tons of water, which is more than the current estimates of groundwater reserve in the region (75.4 billion tons; Ministry of Water Resource of China 2012). The impact of climate change may further exacerbate the water shortage in NCP (Piao et al. 2010). Furthermore, the fast developing animal and vegetable production sectors in the region have been and will continue to dry up the aquifers faster. In addition, rapid urbanization and industrialization will increase water transfers from low-value agricultural uses to high-value industrial and domestic uses (Matsuno et al. 2007). Resolving the water shortage issue systemically therefore is absolutely critical to the region's future development, particularly in agriculture.

Reducing water use without decreasing crop production is difficult because evaporation from crops is tightly coupled with the capture of carbon. A limitation in water supply to decrease transpiration below the rate regulated by the evaporative demand of the natural environment will dry the soil and limit plant growth. Deficit irrigation appears to be an effective management approach, particularly for areas with water shortage such

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as NCP. This is achieved by using deficit irrigation to regulate excessive vegetative vigor and to shift the balance between grain/fruit and vegetative growth toward sustained production of high-quality grain/fruit thereby delivering a substantial dividend in terms of crop value (Davies et al. 2002). The extent of grain filling in monocarpic cereals depends on carbon from two sources: current assimilates and assimilates redistributed from reserve pools in vegetative tissues (e.g., stems and leaf sheaths). Remobilization of reserves from these stores to the grain can contribute as much as 40% of rice yield. High applications of nitrogen fertilizer can delay crop senescence and prevent remobilization thereby reducing grain yield. Yang and Zhang (2010) have shown that deficit irrigation helps stimulate senescence, enhance resource remobilization and thereby increase Harvest Index and grain yield.

Several approaches to deficit irrigation have proved successful for various crops (see, e.g., Chaves et al. 2007; Fereres and Soriano 2007). In China in particular, these techniques have impacted very positively on water productivity, catchment hydrology, and the quality of the natural environment. Kang and Zhang (2004) have developed a novel irrigation method termed controlled alternate partial root-zone irrigation (CAPRI). This technique, exploiting plant's drought stress biology (Gowing et al. 1990), can improve crop water use efficiency substantially and save significant quantities of water. In a range of experiments in China, CAPRI maintained high grain yield with up to 50% reduction in irrigation water use. Conventional irrigation with the same reduced amount of water delivered a substantial decrease in yield. The technique was extended to over 4000 ha of cereals in northwest China. In one region of over 1000 ha two million m^3 of irrigation water was saved and substantial electric energy for pumping groundwater was also saved.

The Yangtze region faces a different issue, where competition for land from the nonagricultural sector has been particularly fierce. Grain production acreage has declined substantially since 1987, due largely to rapid municipal and industrial growth in Yangtze region such as Shanghai, Jiangsu, and Zhejiang province (Long et al. 2007). Take Jiangsu province for instance, urban settlements, rural settlements, and industrial land increased by 87,997 ha (175%), 81,041 ha (105%), and 12,692 ha (398%), respectively, from 1990 to 2006. Previous rice paddy fields and dryland contributed to newly urbanized areas by 37.12% and 73.52% during 1990–2000, and 46.39% and 38.86% during 2000–2006 (Liu et al. 2010). Arable land in the Yangtze region decreased from 25.3 Mha in 1996 to 23.9 Mha in 2008, the decrease averaging −0.5% per year. If the output of rice is increased by 20.6 MT, the cultivated area would need to increase by 3.1 Mha from the yield of rice achieved in 2011. If wheat output increases by 19.1 MT, more than 4.1 Mha of additional cultivated area will be needed on top of the 5.7 Mha currently used for wheat production. Therefore, increases in grain output in the Yangtze region will become increasingly difficult.

General Discussion

China has made a remarkable stride in the past six decades in increasing grain production and enhancing its food security, thanks to the "green revolution" in genetic improvement along with accelerated resource inputs, advances in nutrient management on grain production system, and what for the most part have been effective and supportive agricultural policies (Table 2).

Agricultural production in China was largely fragmented and staggering due to the long-term war prior to 1949. Between 1949 and 1977, the "People's Commune" system was mandated by the government as a way to solve the problem of low efficiency of the grain production of small household farmers. Under this system, massive amounts of labors were organized to cultivate wastelands, reclaim land, and conduct farmland water conservancy projects in order to expand farmland and irrigated area. Consequently, the total cultivated area for grain production increased from 110 to 120 Mha, around 9.5%. Irrigated area in China increased from 20 Mha (less than 20% of the total area of farmland in 1952) to 50 Mha (more than 40% of the total area of farmland by the end of 1978). Meanwhile, over 7 Mha of terraced fields were constructed. Due to an almost total absence of agricultural machines and fertilizers, these substantial increases in grain production were largely achieved through the increased irrigation and manure inputs.

The People's Commune system significantly promoted grain production. However, it greatly diminished the individual farmer's autonomy because the government removed the farmers' rights to trade their own grain output. In the last several years of the 1970s, increase in cereal production was very limited. Therefore, bold policies and institutional reforms were implemented to motivate greater production by rural households (Fan et al. 2004). In 1978 the government introduced the household responsibility system, under which key land rights were reallocated from collective farms to rural households and the households were required to sell the grain to the government with some specified quota amount at contract prices in exchange for use rights to specific plots of land (Shea 2010). As long as the quota obligations are met, farmers are generally free to grow whatever crops they desire and to sell their harvest at the market price. During the 6 years from 1978 to 1984, the average annual increase in the national grain yield was 4.9%, which was the highest rate since 1949.

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Table 2. The policy transformation of grain production between 1949 and 2011.

Phases	Policy description	Cultivated[1] area (Mha)	Irrigated[1] area (Mha)	Chemical[1] fertilizers (kg ha^{-1})	Agricultural[1] machine (MkW)
Phase I (1949–1977)	Government control from grain production to distribution;People's Commune	110–120	<20–45	0.6–73.4	<0.2–103
Phase II (1978–1984)	Household responsibility system	121–113	45–44	73.3–154	117–195
Phase III (1985–1998)	Household responsibility system; liberation of rural market	109–114	44–52	163–294	209–452
Phase IV (1999–2003)	Household responsibility system; marketization of grain production	113–99	53–54	299–303	490–604
Phase V (2004–2011)	Household responsibility system; marketization of grain production; subsidy policy	101–111	54–62	287–345	640–977
2011-beyond	Market + technology + service + policy	No change	No change	Reduce	Increase

[1]The data of cultivated area, irrigated area, chemical fertilizers, and agricultural machines were collected from the China Statistical Yearbook published by National Bureau of Statistics of China in 2012.

During the period 1985 and 1998, the Chinese government tried to promote the marketing of agricultural products, which mobilized the farmers' enthusiasm for grain production further. Farmers were anxious to increase input of agricultural materials as much as possible in order to expand grain production. Pesticide use increased by >65%, and the use of fertilizers and agricultural machinery (mainly small tillage and harvesting machine for small farmers) doubled. In 1994, China became the world's largest consumer of chemical fertilizers. Meanwhile, the Chinese government implemented a market reform policy to lower the grain acquisition price and remove price control on other crops and animal products, which expanded the proportion of other crops and animal production. This policy caused many farmers to convert from cereal production to the production of cash crops. During the period 1999 and 2003, the central government withdrew from management of national cereal production and storage; this caused a decrease in the national cereal planting area of 12.2%. The annual growth rate fell to the historical low value of −4.1%.

In 2004, the Chinese government started to encourage grain production once again with a series of policies such as subsidy on grain production, fertilizers, and other agricultural materials, using new varieties, and purchasing of agricultural machinery. The government also canceled agricultural tax. In addition to economic incentives and exemptions, the central government commanded provincial governors and mayors to be directly responsible to ensure consistent supplies of basic food. Hence, farmers were once again motivated to produce extra grain. In 2004, China's grain production recovered from a 5-year consecutive decline since 1998 and entered a recovery stage. The annual growth rate of grain yield between 2004 and 2011 was 2.6%, while the corresponding rate in the rest of the world was 1.1%. While these subsidies promoted massive inputs of agricultural resources by farmers, the crop yield was not improved to the same extent due to a lack of agricultural technology and modern cultivation methods. For instance, the nationwide application of N fertilizers was 30–60% above that of agronomically sound and environmentally sensible recommendations. The problems caused by excessive applications were compounded by application made at inappropriate times of the growing season (e.g., for wheat, 60% of the N was applied before planting and 26% of farmers reported single application times instead of split applications). Hand-broadcasting methods were also employed (surface spreading of fertilizers before soil preparation or irrigation) (Zhang et al. 2013). This kind of fertilizer application will not contribute much to increased crop yield but will potentially generate a range of environmental problems, such as greenhouse gas emissions, soil acidification, and N-deposition (Guo et al. 2010; Liu et al. 2013; Zhang et al. 2013). In the future, China must address the following four issues if it is to ensure its food security: (1) How to improve farmers' initiatives for grain production? (2) How to further boost crop yield? (3) How to eliminate/minimize the environmental costs of grain production? (4) How to recouple grain production with animal production to better recycle manures and protect water quality? The approach to these key questions must be based on effective technical schemes and development of effective extension systems, and policy options.

Integrated technology for greater yield as well as efficiency

There remains a large yield gap within China. For maize, farmer's yields average 7.9 t ha^{-1} but the yield potential

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is 16.5 t ha^{-1} with the best recorded yield being 15.4 t ha^{-1} (Shen et al. 2013a). The large yield gap is caused by the climate and natural resources constraints, poor water and fertilizer management, and improper crop cultivation practice. Hence, scientists specializing in crop improvement and in advanced crop management techniques (crop cultivation and soil and nutrient management) should collaborate in order to design applicable and optimized technologies to best fit local conditions including root/rhizosphere management (Shen et al. 2013b). Plant breeders need to produce more efficient and productive varieties with increased yield potential (e.g., Reynolds et al. 2010). Agronomists need to develop novel crop management techniques such as manipulating root growth as well as designing better crop canopy (Shen et al. 2013b); soil scientists need to integrate tillage, sustainable fertilizer use, incorporation of crop residues, use of soil amendment, and novel crop rotation practices, and plant nutrition experts should design effective nutrition management systems based both on soil nutrient supply capacity and nutrient requirements of the plant. Efficient extension systems should be established to promote and deliver novel integrated technologies into the hands of hundreds of millions of farmers. Currently, the extension rate for novel technologies applied to grain production is only 35%, and the contribution of the technology to enhanced grain production is around 30–40% in China. In contrast, the rate in many developed countries is as high as 60–80% (Wei 2009). This suggests that economists and sociologists should cooperate to develop a market-oriented extension system designed for different technological integration models and cost-benefit situations for farmer households. In addition, supporting policies, including subsidies, are needed for the application of highly productive and effective technologies.

Infrastructure building and supporting policies

Urbanization and development of related infrastructural support have been much enhanced in China during the past few decades. However, in rural China, the development of infrastructure has lagged behind. For instance, irrigated land accounts for 55% of the total cultivated crop acreage but irrigation systems are often remarkably low in water use efficiency. Due in part to obsolete equipment and facilities, roughly 50% of the water resource is commonly lost during the process of transportation. Investment in irrigation, with both strategic expansion of irrigated land and enhancement of water use efficiency is essential to promote future crop yield. Furthermore, the small size of individual Chinese farms makes it difficult to use some advanced technologies such as mechanized ploughing and fertilization. In addition, migration of younger people to cities has caused labor shortages in parts of rural China. Moreover, growing demand for animal products and its link to grain production in the future will intensify the competition of water and land use between grain and animal production. In response, to all of this, farmers' cooperatives have emerged in recent years, the reconsolidation of small plots of land into large farms increases efficiency of many cultural processes. Developments such as these might be encouraged by government with support offered through scientific and technological inputs. In addition, road construction in rural China would substantially benefit agricultural development. Furthermore, use of agricultural by-products, such as animal and human wastes, crop residues, green manure, and city sludge is essential to improve soil quality and reduce use of inorganic fertilizers, but many farmers are unwilling to use these organic wastes due to lack of necessary facilities for transportation and distribution. Government intervention to encourage waste processing (storage system and nonhazardous treatment) instead of current "direct discard" practice could be very important for food security and environment safety. Finally, investment in small irrigation and water conservancy infrastructure, land integration, and development of mechanical farming can bear dividends.

Motivating farmers for enhanced productivity

Due to the low-pricing policy for crop products in China, food production is a low profitability business in general. Farmers are attracted to cities for the cash reward of nonagricultural jobs. There is a lack of economic incentive for farmers to spend time and money on new technologies for grain production. Although the government encourages farmers to participate in farming through a series of subsidy programs, these subsidies fail to encourage farmers to use more advanced technology for enhanced productivity. From the perspective of the subsidy on per unit land, in 2008 Chinese farmers received a subsidy at 34.4 USD/acre, which is similar to what an American farmer would receive from the US subsidy program (at 30–50 USD/acre) (Huang et al. 2011b). However, the average Chinese farm household only farms 1.5 acre of land, making the seemingly substantial subsidies trivial for an average Chinese farmer (Chen et al. 2011). Also, ongoing differentiated subsidies have resulted in the change in cropping structure, reducing the areas committed to soybeans and oil plants. If food production is to continue to increase, the present policy on subsidies needs to be adjusted, and infrastructure construction needs to be subsidized (not just facilities for agricultural production, but also including roads, communication and

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energy), prices of agricultural products should be protected, extension systems must be developed, agricultural credit systems must be established, and farmer cooperatives should be encouraged. These measures can be crucial to motivate farmers, promote technological advances, and to safeguard the increase in food production.

Conclusion

At present, China's food security is relatively sound at the national level. However, future food security is threatened by anthropogenic (Wilkinson et al. 2012), sociopolitical and policy factors. In addition, soil degradation, water scarcity, severe pollution, and declining efficiency of fertilizer application have become more and more prominent as the consequences of the current grain production development model. How to sustainably support a growing population and its changing appetite and dietary needs has been a concern and will continue to be high priority on the national policy agenda. The technology currently adopted for crop production does not generate maximum efficiency; but on the other hand, it provides huge potential to increase the unit production in China. Future adoption of an integrated management technology could be one way of boosting grain production for years to come. Therefore, innovations in both policy formulation and technology can be promoted for the sustainability of grain production in China. Government investments in agriculture must lean toward some technology extensions, households should be encouraged in particular to use new agricultural technology, and useful knowledge on utilization of resources should be wildly available to help farmers make full use of resources under a limited resource budget. Policies of this kind should be combined with both environmental considerations and active consideration of new social policies aimed at increasing the availability of good quality safe food. Particular attention should be given to ensure that evolving dietary changes are both environmentally sustainable and health promoting.

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Conflict of Interest

None declared.

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