15 Current Status and Future Perspectives to Increase Nutrient- and Water-Use Efficiency in Food Production Systems in China

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Historical Changes and Future Challenge of Crop Production

Arable farming of cereal crops began in China at least 3,000 years ago along the middle and lower reaches of Yangtze River and Yellow River (Xu et al. 1991; Li 2001). The long history of arable farming and ever-increasing human population has led to the depletion of arable land reserves (Li & Sun 1990). For example, the population of China has more than doubled since the 1950s to its current level of 1.3 billion, but the total arable land area has expanded by only 29% to the current 134.5 million ha. The per capita arable land area is 0.1 ha at present, which is 45% of the world average (Fan et al. 2010).

Despite the limited land resources, cereal production in China has grown markedly in the last four decades. Cereal production increased steadily from 83.4 Mt in 1961 to 474 Mt in 2009. The net increase was 391 Mt with an annual growth rate of 3.7% (Figure 15.1). China accounted for about 29% of global rice production, 15% of maize, and 24% of wheat production (Food and Agriculture Organization [FAO] 2006; National Bureau of Statistics of China 2007).

The increase in total crop production in China has arisen mainly from an increase in yield per unit area rather than in the area under cultivation. For example, from 1961 to 2009 the yield increase was 3.2 times for rice (from 2,041 to 6,585 kg/ha), 8.5 times for wheat (from 557 to 4,739 kg/ha), and 4.6 times for maize (from 1,139 to 5,258 kg/ha). Over the same period the total cultivated area under cereals increased by 30% (from 65.5 million ha in 1961 to 85.1 million ha in 2009).

One main reason for fantastic improvement in crop yield per unit area was intensification of crop production by using improved germplasm, greater inputs of chemical fertilizers, production of two or more crops per year on the same area of land, irrigation, and weed and pest control (Fan et al. 2011).

The consumption of fertilizer has increased linearly since 1961. The total consumption of chemical fertilizers in China exceeded 64 Mt in 2009, nearly 35% of the total global consumption (Consumption = production + import − export; revised from National Bureau of Statistics of China 1961–2009). Irrigated farmland has expanded by 32% since 1978; the current effective irrigated farmland reached 58.5 million ha, which is 48% of the total arable land area, but it produces 75% of the national grain and 90% of products from cash crops (National Bureau of Statistics of China 2008). Usage of chemicals such as pesticides and herbicides increased from 0.76 Mt in 1991 to 1.76 Mt in 2005. As the second largest producer and consumer of pesticides, China accounts for 14% of the world total production and has become a net exporter (Liu & Diamond 2002).

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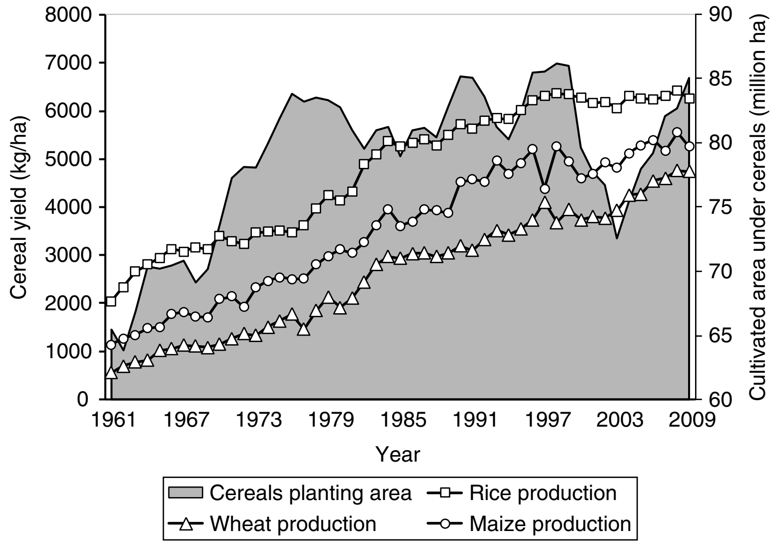

Figure 15.1 Changes in total cereal harvest area and grain yields of rice, maize, and wheat in China from 1961 to 2009. *Source*: FAO STAT electronic databases (http://apps.fao.org); China Agriculture Yearbook 1961–2009.

The shorter duration of high-yield varieties allows annual double- and triple-crop systems in warmer regions that have long growing seasons. Indeed, most rice, maize, and wheat in China are now produced in double systems, whereas only a single annual crop was possible 30 to 40 years ago.

Looking toward 2030, even assuming that the Chinese population stabilizes at 1.6 billion, to meet the demand for grain and to feed a growing population on the remaining arable land, crop production must reach 580 Mt, and yield has to increase by 2% annually in China (Fan et al. 2010). With the technology that is currently being used, it appears impossible to increase production to the level that is needed. Furthermore, increased crop production will face multiple pressures stemming from resource limitation and environmental pollution (Fan et al. 2011).

The Chinese government regards agriculture as the primary field of development of the national economy in the 21st century. The optimal agricultural development path for China is to improve the ratio of resource use (e.g., nutrients and water) and protect the environment while guaranteeing the grain supply.

The Current Status of Fertilizer- and Water-Use Efficiency

Fertilizer Applications and Fertilizer-Use Efficiency in Cropping Systems

China has a long tradition (thousands of years) of recycling organic materials to maintain relatively high yield levels and prevent soil fertility from declining. Before 1949, almost no inorganic fertilizers were used in China, but the situation has now changed significantly. Calculated changes in fertilizer inputs in China from 1961 to 2009 are shown in Figure 15.2. The consumption of fertilizer nitrogen (N), phosphorus (P), and potassium (K) increased almost linearly from 5, 0.1, and 0 Mt, respectively, in 1961 to 46.6, 12.5, and 4.8 Mt, respectively, in 2009 (Revised from National Bureau of Statistics of China 1961–2009).

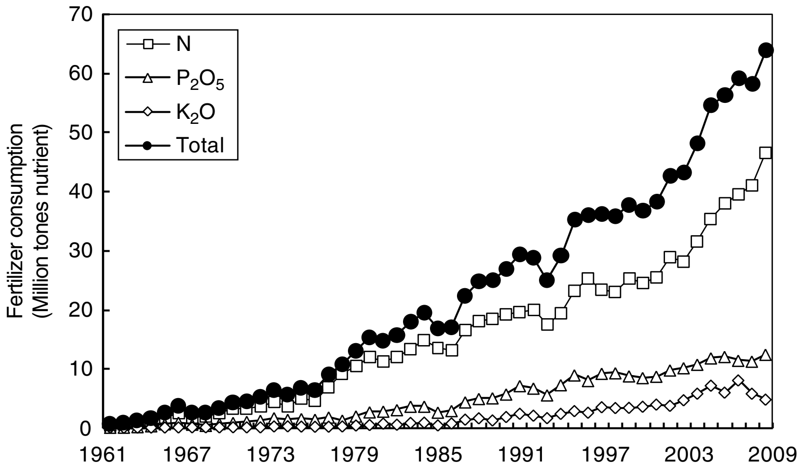

Figure 15.2 Trends in chemical fertilizer consumption in China from 1961 to 2009. The consumption is the apparent consumption across the whole China calculated as: production + imports – exports.
Source: China Statistic year book 1978–2010.

Table 15.1 The N fertilizer rates for cereal crops and cash crops (i.e., vegetables, fruits, and flowers) in selected locations and years in China.

Location and years	Cropping system	N rate (kg N/ha)	Reference
Average across China, 2002	Wheat	204	Li et al. 2010
	Maize	199	Li et al. 2010
	Rice	217	Li et al. 2010
Average across China, 2007	Wheat	229	Li et al. 2010
	Maize	237	Li et al. 2010
	Rice	231	Li et al. 2010
Average across China, 2006	Rice	193	Roelcke et al. 2004; Peng et al. 2010
North China plain, 2000	Wheat-maize	670	Zhen et al. 2006
Shan Dong province, 1997 and 1998	Greenhouse field/Vegetables	1,700	Ma 1999
Beijing, 1996–2000	Open field/Chinese cabbage	607	Chen et al. 2004
Beijing, 1996–2000	Open field/Cucumber	882	Chen et al. 2004
Beijing, 1996–2000	Greenhouse field/cabbage	440	Chen et al. 2004
Beijing, 1996–2000	Greenhouse field/sweet pepper	1,068	Chen et al. 2004
China, 2001	Cash crops (vegetables, fruits and flowers)	569–2000	Price Department of National Development and Reform Commission, 2001

Excessive application of chemical fertilizers, especially N fertilizers, has been a common problem in intensive agricultural regions of China. Table 15.1 shows the N fertilizer rates for cereal crops and cash crops (i.e., vegetables, fruits, and flowers) in selected locations and years in China. For example, the average amount of N applied for the winter wheat–summer maize double-cropping system in the north China plain increased from 143 kg/ha in 1967 to about 384 kg/ha in 1988 and 670 kg/ha in 2000 (Zhen et al. 2006). The average N application rate for rice (*Oryza sativa* L.) in China was 193 kg/ha in 2006, but rates from 150 to 250 kg/ha are common now and can reach 300 kg/ha in some places (Roelcke et al. 2004; Peng et al. 2010). Based on a countrywide on-farm survey, Li et al. (2010) found that N fertilizer rates for cereal crops showed an increasing trend: the rates were 204 kg/ha for wheat, 199 kg/ha for maize, and 217 kg/ha for rice in 2002 and 229 kg/ha for wheat, 237 kg/ha for maize, and 231 kg/ha for rice in 2007.

Farmers in China are encouraged to convert cereal fields to vegetable production because of changing consumer demands as incomes rise (Lei et al. 2010). As a result, vegetable production has developed rapidly since the 1980s. Today, China is the world leader in vegetable production and consumption, with an area of 18.4 million ha dedicated solely to vegetable production (National Bureau of Statistics of China 2009). Nutrient inputs, especially N, are much higher in vegetable production systems than in cereal production. Ma (1999) reported that the average N application rate was 1,700 kg/ha per crop for protected vegetable fields (plastic greenhouses) ($n = 147$) in Shandong Province based on surveys conducted in 1997 and 1998. Chen et al. (2004) found that the average total N application rate for both organic manure and chemical fertilizers varied from 607 kg N/ha for Chinese cabbage (*Brassica chinensis* L.) to 882 kg N/ha for cucumber (*Cucumis sativus* L.) in open fields, and from 440 kg N/ha for cabbage (*Brassica oleracea* var. *capitata* L.) to 1068 kg N/ha for sweet pepper (*Capsicum annuum*) in greenhouses, based on surveys conducted from 1996 to 2000 in Beijing. According to another investigation conducted throughout the country, the average N application rate for high value crops (i.e., vegetables, fruit trees, and flowers) was 569 to 2,000 kg N/ha (Price Department of National Development and Reform Commission 2001).

In addition to excessive rates, chemical fertilizer application is often not based on the real-time nutrient requirements of the crop or site-specific knowledge of the soil nutrient status. For example, in rice production systems most farmers apply N in two portions (basal and top-dressing) within the first 10 days of the rice growing season (Fan et al. 2007). In the intensive wheat–maize system in China, applying large amounts of N fertilizer before planting or at the early growth stage constitutes standard management practice to ensure adequate N for the whole growing season, and this basal N supply rate is usually about 50% of the total amount given (Cui et al. 2008). This large amount of basal fertilizer N is prone to losses over an extended period because the plants require time to develop their root systems and a significant demand for N.

Nutrient (i.e., NPK) efficiency is quite low in China. This may be attributed to fertilizer overuse and high nutrient losses resulting from inappropriate timing and methods of fertilizer application, especially in high-yielding fields. Zhang et al. (2008) evaluated the current status of nutrient efficiency at the national scale by pooling and analyzing numerous data sets from published papers (Table 15.2). The partial factor productivity of applied N (kg grain/kg N) is 54 for rice, 43 for wheat, and 52 for maize. Apparent recovery efficiency of N (percent of fertilizer N recovered in above-ground crop biomass [ARE]); see also Table 16.8 in this volume) for cereal crops was 35% on average in the 1990s. However, this value has gradually declined since then and the current ARE is 28% for rice and wheat and 26% for maize, all of which are lower than the world averages (40%–60%).

Inappropriate fertilizer application has led to environmental pollution. For example, losses of N and P through leaching and run-off have caused drinking water pollution, affecting 30% of the population and resulting in eutrophication of 61% of lakes in the country. Agricultural production also results in considerable emissions of nitrogen oxides to the atmosphere (Fan et al. 2010).

The key question is why farmers in China use fertilizers so much and consequently achieve low nutrient-use efficiencies. Miao et al. (2010) attributed this mainly to: (1) high yield as the top priority with little attention being paid to nutrient-use efficiencies, economic returns, or environmental risks, (2) small-scale farming discouraging farmers to adopt advanced farming technologies, (3) lack of temporal synchronization between nutrient application and crop demand, especially for N, (4) lack of effective knowledge-extension systems, and (5) lack of proper fertilizer-application machinery.

Table 15.2 Fertilizer application rates, grain yields, and various nutrient-use efficiencies for rice, wheat, and maize.

Crop	Nutrient	Fertilizer rate (kg/ha)	Yield (kg/ha)	PFP (kg/kg)	AE (kg/kg)	ARE (%)	PE (kg/kg)
Rice	N	150	6,835	54	10.4	28	37
	P	39.5	6,779	99	9.0	13	69
	K	71.6	6,823	99	6.3	32	19
Wheat	N	169	5,721	43	8.0	28	28
	P	49.8	5,704	64	7.3	11	68
	K	91.3	5,605	72	5.3	30	17
Maize	N	162	7,045	52	9.8	26	38
	P	49.8	6,620	72	7.5	11	68
	K	96.3	6,012	65	5.7	32	18

Note: (for details on calculations see table 16.8 in this volume).
AE, agronomic efficiency of nutrient (kg grain yield increase per kg nutrient applied); ARE, recovery efficiency of nutrient (% fertilizer nutrient recovered in aboveground crop biomass); PE, physiological efficiency of applied nutrient (kg yield increase per kg increase in nutrient uptake from fertilizer); PFP, partial factor productivity of applied nutrient (kg grain per kg nutrient applied).
Source: Reprinted with permission from Zhang, F., Wang, J., Zhang, W., et al. (2008) Situation and countermeasures of nutrient utilization efficiency for major cereal crops in China. *Acta Pedologica Sinica*, **45**, 915–924.

In conclusion, optimization of nutrient application and achieving greater nutrient-use efficiency at national and provincial levels are urgently required in China. This will require policies that favor increases in nutrient-use efficiency at the field scale with an emphasis on technologies that can achieve greater congruence between crop nutrient demand and nutrient supply from all sources, including fertilizer (chemical and organic) inputs and native soil nutrients.

Water Availability and Water-Use Efficiency in Cropping Systems

Irrigated farmland accounts for 75% of the national grain production and 90% of products from cash crops (National Bureau of Statistics of China 2008). However, of all environmental woes in China, the biggest threat to livelihoods and food security may be looming water shortages (Li 2010). China's total fresh water volume is 2.81×10^{12} m^3, with 2.7×10^{12} m^3 of surface water and 0.83×10^{12} m^3 of groundwater (The Ministry of Water Resources of the People's Republic of China 2009). Although this water resource is large in the absolute terms, ranking sixth in the world, the per capita water resource is only 25% of the world average (Wang et al. 2008). China is listed as one of the 13 countries in the world with most severe water shortages. Moreover, the distribution of water resources is spatially and seasonally uneven. The north of the country, similar in land area and population to the south, holds only 18% of the total water despite having 65% of the total arable land. Notably, the south receives water predominantly from summer rainfalls, often "wasted" through flooding (Piao et al. 2010).

Agricultural water use represents the main part of the national water resources. Of total agricultural water use, irrigation (green water) and rainfall (blue water) account for 46% and 54%, respectively (Li & Peng 2009). However, increased water shortage associated with overuse of surface water, declining groundwater levels, water pollution, and soil salinization are threatening the sustainability of agricultural production. The water supply for agricultural production will unavoidably decrease with the increasing demands from domestic and industrial water users. The share of irrigation in total water use in China has declined from 80% in 1980s to 65% presently (The Ministry of Water Resources of the People's Republic of China 2009). Annual water shortage in agriculture is estimated at 30 billion m^3 in China.

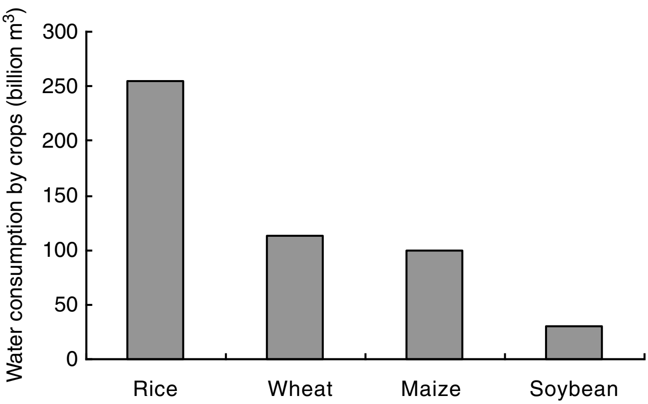

Figure 15.3 Water consumption by cereal crops in China during 1998–2007.
Source: Li & Peng (2009).

The outlook is especially dire on the north China plain (NCP), one of the main grain production areas in China, representing 34% of the national arable land but having only 3.9% of the national water resources. Over the past 40 years, NCP's water table has fallen steadily as some 120 billion m^3 more water was pumped from the land than the amount replaced by rainfall (Li 2010).

The agricultural water-use efficiency (WUE) defined as grain produced by unit water consumed (WUE = grain yield/evapotranspiration, kg/m^3) is low because of the poor irrigation management practices (Wang et al. 2002; Deng et al. 2006) and a lack of investment in infrastructure (Xu & Zhao 2001; Lohmar et al. 2003). Li and Peng (2009) evaluated the current status of water consumption and WUE by food crops at both national and provincial scales from 1998 to 2007 by analyzing data sets of China Water Resources Bulletin and China Agricultural Statistics Yearbook. The average water consumption of food crops in the period 1998–2007 was 499 billion m^3, of which rice accounted for 51% (255 billion m^3), wheat 23% (114 billion m^3), maize 20% (100 billion m^3), and soybean 6.2% (3.1 billion m^3) (Figure 15.3). The water consumption in different regions was in the following order: southeast (160 billion m^3), north (114 billion m^3), southwest (85.6 billion m^3), northeast (74.9 billion m^3), and northwest (64.9 billion m^3) (Figure 15.4). The highest water consumption is in the southeast because rice is the main crop. In contrast, rain-fed agriculture is dominant in the northwest, so water consumption is lowest among the above regions.

As shown in Table 15.3, the average WUE of three main grain crops in China was 1.12 kg/m^3, with 0.85 kg/m^3 for rice, 1.01 kg/m^3 for wheat, and 1.51 kg/m^3 for maize (Li & Peng 2009). In another study based on data from 4,422 sites across 22 provinces in China, the averaged WUE values were estimated at 1.1 kg/m^3 for the cereal crops under well-irrigated conditions (Duan & Zhang 2000). However, Zwart and Bastiaanssen (2004) reviewed 84 literature sources from around the world with results of experiments not older than 25 years and found that the average WUE was 1.1 for wheat and rice and 1.8 kg/m^3 for maize. Thus, the overall WUE in grain production in China fell behind the world level. Furthermore, Duan and Zhang (2000) showed that WUE in farmers' fields is generally lower than on the experimental sites because of the irregularity and deficit of irrigation amounts and limitations caused by soil nutrients, pests, and weeds. These results imply there are tremendous opportunities to reduce water consumption with no or little reduction in grain yield (Wang et al. 2002; Hu et al. 2006), thereby increasing WUE.

To save water and maintain food security, researchers have proposed improved water conservation, better water pricing policies, and rational agricultural practices such as drip and sprinkler irrigation and no-till farming. However, combining various management practices should be more effective in improving WUE than any single management. Understanding the variations in WUE associated

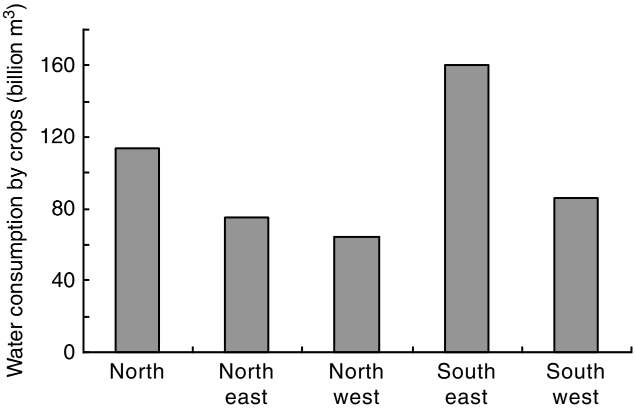

Figure 15.4 Water consumption by region in China during 1998–2007.
Source: Report of water resource from 1998 to 2007 in China.

Table 15.3 Water-use efficiency of main cereal crops in selected locations and years in China.

Location and years	Crop type	Water use efficiency (kg/m^3)*	Reference
Average across China for irrigated farmland, 1980–1986	Early rice	0.72	Duan & Zhang 2000
	Single rice	0.71	Duan & Zhang 2000
	Later rice	0.63	Duan & Zhang 2000
	Winter wheat	1.33	Duan & Zhang 2000
	Spring Wheat	0.80	Duan & Zhang 2000
	Summer maize	1.70	Duan & Zhang 2000
	Spring maize	1.74	Duan & Zhang 2000
Average across China for irrigated farmland, 1998–2007	Rice	0.85	Li & Peng 2009
	Wheat	1.01	Li & Peng 2009
	Maize	1.51	Li & Peng 2009
North China plain, 1997–2005	Winter wheat	1.30–1.70	Zhang et al. 2006
	Summer maize	1.50–2.0	Zhang et al. 2006
North China, 2007	Spring maize	1.9–2.2	Liu et al. 2009
Northwest China, 2001	Rice	1.04–1.1	Liu et al. 2005
South China, 2007	Rice	1.0–1.29	Jia & Lu 2010

*Water use efficiency = grain yield/evapotranspiration.
Source: Reprinted with permission from Zhang, F., Wang, J., Zhang, W., et al. (2008) Situation and Countermeasures of Nutrient Utilization Efficiency for Major Cereal Crops in China. Acta Pedologica Sinica, 45, 915–924.

with soil and climate conditions can also contribute to the transfer of irrigation technology to farmers and to optimizing regional water management in agriculture (Fang et al. 2010).

Future Perspectives for Increasing Nutrient- and Water-Use Efficiency

Integrated Soil-Crop Systems Management

Greater advances in crop production are needed during the coming 20 years to achieve a substantial increase in grain yields and ensure food security. Toward this, the science of crop and soil management and agricultural practice also needs to be given particular emphasis as part of a food-security grand challenge (Baulcombe et al. 2009). Despite the enormous importance of the subject and the growing number of specific studies, multidisciplinary synthesis of the knowledge of agronomy, soil science, and agro-ecology (the relevant sciences in crop production) is scarce in China (Fan et al. 2011). The development of more ecologically based agricultural systems that reintegrate features of traditional agricultural knowledge and add new ecological knowledge into the intensification process will be needed (Matson & Vitousek, 2006).

Here, we advocate an integrated soil-crop system management approach addressing key constraints such as low soil fertilizer, water shortage, low nutrient-use efficiencies, and impacts of climate change in further improving crop production with efficient resource use in China. In this approach, the key principles include (1) considering all possible measures for improving soil quality, (2) integrating use of various nutrient resources and match nutrient supply to crop requirements, and (3) integrating soil and nutrient management with high yielding cultivation systems (Zhang et al. 2011).

Chen et al. (2011) established "integrated soil-crop system management for maize" (ISSM) to design optimal crop and nutrient management for given ecological conditions by using (1) hybrid-maize simulation model to maximize the use of solar radiation and temperature (Yang et al. 2004), and (2) a root-zone in-season N management strategy to synchronize N supply from soil and fertilizer and N demand by the crop (Chen et al. 2006). The current studies showed that this ISSM system could achieve 12 t/ha maize grain yield with 260 kg N/ha fertilizer application. This yield level was twice the yield achieved with farmers' practice, whereas the amount of N fertilizer applied was similar to what farmers would use. Thus, N-use efficiency was increased twofold compared with the farmers' practice.

The preceding research with maize has illustrated a potential for the substantial improvements in yield with higher input efficiency. These ISSM approaches address key constrains (e.g., low soil nutrients, water shortage, low nutrient-use efficiencies, and impacts of climate change) in existing crop varieties and can be applied widely. However, much more is required in development of ISSM countrywide. The key points are: (1) multidisciplinary cooperation among soil scientists, agronomists, ecologists, and so on and (2) greater understanding of interactions among soils, crops, and the environment (Fan et al. 2011).

Genetic Improvements for Nutrient- and WUE

To achieve the goal of increasing crop production in a sustainable manner in China, it is a promising approach to grow crop cultivars that achieve high yield with reduced inputs of water and fertilizer resources. This leads Chinese plant breeders to focus much more on the traits of WUE and nutrient-use efficiency, including both uptake and use efficiency. Since the early 1990s, significant efforts through a traditional breeding approach have been made toward selecting and identifying favorite genotypes adapted to water and nutrient limitations from the germplasm collected from different areas of China. Based on these valuable breeding materials, P-efficient wheat cultivar (Xiaoyan 54) and soybean cultivar (BX10), and N-efficient maize hybrid (Zhongnong 99, Figure 15.5) were developed and are currently widespread in Chinese croplands (Yan et al. 2006; Chen et al. 2009).

P-efficient wheat Xiaoyan 54 and soybean BX10 were improved with the genetic material from their wild relatives, indicating that expanding the germplasm base for nutrient-use efficiency is essential for our breeding processes. It is worth noting that all these efficient cultivars formed large root systems, implicating that modification of crop roots could offer an effective way to enhance water and nutrient acquisition. Although its primary target is always grain yield potential, the traditional breeding approach has the capacity to contribute to improving WUE and nutrient-use efficiency of crops in China.

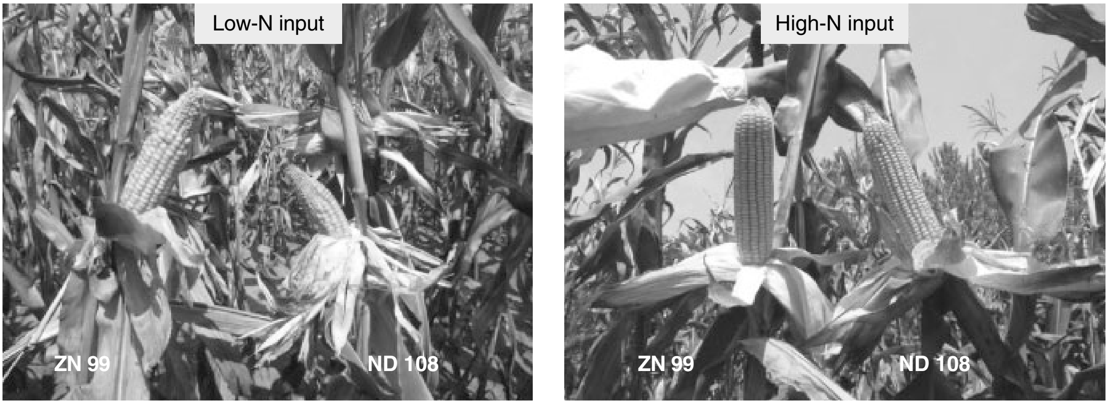

Figure 15.5 N-use efficient hybrid ZN99 developed by China Agricultural University. Compared with control hybrid ND108, N-use efficient hybrid ZN99 achieved a significantly higher yield (about 25%) under low-N inputs but only about 3% higher under high-N input. N, nitrogen. For color detail, please see color plate section.
Photo by Dr. Fanjun Chen, China Agricultural University, Beijing.

Given the complexity of the WUE and nutrient-use efficiency traits in crops, the power of traditional breeding approach has been limited. Traditional breeding methods need to be combined with advanced breeding technologies such as marker-assisted selection (MAS) and genetic modification (GM). Instead of identifying and selecting the complex phenotypes for WUE and nutrient-use efficiency during the breeding process, MAS is an efficient way to accelerate the introduction of the desired traits into elite lines from many different sources. The MAS approach replies on the discovery of genes or quantitative traits loci (QTL) associated with the traits contributing to WUE and nutrient-use efficiency.

This allows for more efficient selection of favorite germplasms across multiple traits and accelerates the breeding cycles. China has the largest plant biotechnology capacity outside North America (Huang et al., 2002). Since 2008, the Chinese government has rolled out a $3.5 billion research and development (R&D) initiative on GM plants (Stone, 2008). Challenges ahead are to: (1) identify the candidate genes and traits valuable for breeding; (2) incorporate these into elite cultivars and to evaluate their performance under real agricultural field conditions (Zhang et al. 2007); and (3) adopt new approaches for generating GM crops to reduce the constraints imposed by regulatory approvals and increase consumer acceptance.

Conclusion

In this review, we focus on integrated soil-crop systems management and genetic improvements for increased crop productivity while improving nutrient- and water-use efficiency. However, the biggest gains from improved technology will come most immediately from combinations of improved crops and improved agronomical practices. Furthermore, a broad range of options including social and economic factors such as knowledge extension and access to technologies by farmers also needs to be pursued. Above all, future work will require a multidisciplinary approach that involves not just soil scientists, agronomists, and farmers but also ecologists, policy makers and social scientists.

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References

Baulcombe, D., Crute, I., Davies, B., et al. (2009) *Reaping the Benefits: Science and the Sustainable Intensification of Global Agriculture*. London: The Royal Society.

Chen, F., & Zhang, F. (2009) New varieties of nitrogen use efficiency maize breeding—Zhongnong 99. *Crops*, **6**, 103–104.

Chen, Q., Zhang, X., Zhang, H., et al. (2004) Evaluation of current fertilizer practice and soil fertility in vegetable production in the Beijing region. *Nutrient Cycling in Agroecosystems*, **69**, 51–58.

Chen, X., Zhang, F., Mheld, V., et al. (2006) Synchronizing N supply from soil and fertilizer and N demand of winter wheat by an improved N min method. *Nutrient Cycling in Agroecosystems*, **74**, 91–98.

Chen, X., Cui, Z., Vitousek, P., et al. (2011) Integrated soil-crop management system for food security. *Proceedings of the National Academy of Sciences USA*, **108**, 6399–6404.

Cui, Z., Miao, Y., Zhang, F., et al. (2008) Soil nitrate-N levels required for high yield maize production in the North China Plain. *Nutrient Cycling in Agroecosystems*, **82**, 187–196.

Deng, X., Shan, L., Zhang, H., et al. (2006) Improving agricultural water use efficiency in arid and semiarid areas of China. *Agricultural Water Management*, **80**, 23–40.

Duan, A., & Zhang, J. (2000) Water use efficiency of grain crops in irrigated farmland in China. *Transactions of CSAE*, **16**, 41–44.

Fan, M., Lu, S., Jiang, R., et al. (2007) Nitrogen input, 15 N balance and mineral N dynamics in a rice-wheat rotation in southwest China. *Nutrient Cycling in Agroecosystems*, **79**, 255–265.

Fan, M., Christie, P., Zhang, W., et al. (2010) Crop productivity, fertilizer use, and soil quality in China. In: *Food Security and Soil Quality (Advances in Soil Science)* (eds. R. Lal, & B. A. Stewart), pp. 87–107. Boca Raton, FL: CRC Press.

Fan, M., Shen, J., Yuan, L., et al. (2011) Improving crop productivity and resource use efficiency to ensure food security and environmental quality in China. *Journal of Experimental Botany*, **63**, 13–24.

Fang, Q., Ma, L., Green, T., et al. (2010) Water resources and water use efficiency in the North China Plain: Current status and agronomic management options. *Agricultural Water Management*, **97**, 1102–1116.

Food and Agriculture Organization (FAO). (1961–2006) FAOSTAT Database—Agricultural Production. http://apps.fao.org. Rome: FAO.

Hu, C., Saseendran, S., Green, T., et al. (2006) Evaluating nitrogen and water management in a double-cropping system using RZWQM. *Vadose Zone Journal*, **5**, 493–505.

Huang, J., Rozelle, S., Pray, C., et al. (2002) Plant biotechnology in China. *Science*, **295**, 674–676.

Jia, H., & Lu, C. (2010) Calculation method of field water use efficiency of rice based on the theory of deficit irrigation [in Chinese]. *Transaction of the CSAE*, **26**, 38–41.

Lei, B., Fan, M., Chen, Q., et al. (2010) Conversion of wheat-maize to vegetable cropping systems changes soil organic matter characteristics. *Soil Science Society of America Journal*, **74**, 1320–1326.

Li, B., & Peng, S. (2009) *Reports on Agricultural Water Use in China from 1998–2007*. Beijing: China Agriculture Publishing House.

Li, C., & Sun, Q. (1990) *Soils of China*. Beijing: Science Press.

Li, W. H. (2001) *Agro-ecological Farming Systems in China*. New York: The Parthenon Publishing Group.

Li, J. (2010) Water shortages loom as Northern China's aquifers are suched dry. *Science*, **328**, 1462–1463.

Li, H., Zhang, W., & Zhang F. (2010) Chemical fertilizer use and efficiency change of main grain crops in China. *Plant Nutrition and Fertilizer Science*, **16**, 1136–1143.

Liu, J., & Diamond, J. (2005) China's environment in a globalizing world. *Nature*, **435**, 1179–1186.

Liu, G., Yang, J., Jiang, Y., et al. (2005) Water requirement and water use efficiency of rice under water-saving irrigation [in Chinese]. *Journal of Irrigation and Drainage*, **24**, 49–52.

Liu, M., Tao, H., Wang, P., et al. (2009) Effects of sowing date on growth, yield formation and water utilization of spring maize [in Chinese]. *Journal of Maize Sciences*, **17**, 108–111.

Lohmar, B., Wang, J., Rozelle, S., et al. (2003) *China's Agricultural Water Policy Reforms: Increasing Investment, Resolving Conflicts, and Revising Incentives*. Agricultural Information Bulletins 33643. Washington, D.C.: US Department of Agriculture, Economic Research Service.

Ma, W. (1999) Current status and evaluation of crop fertilization in Shandong Province. Ph.D thesis. China Agricultural University, Beijing.

Matson, P., & Vitousek, P. (2006) Agricultural intensification: will land spared from farming be land spared for nature? *Conservation Biology*, **20**, 709–710.

Miao, Y., Stewart, B., Zhang, F. (2010) Long-term experiments for sustainable nutrient management in China. A review. *Agronomy for Sustainable Development*, **31**, 397–414.

National Bureau of Statistics of China. (1961–2010) *China Agriculture Yearbook*. Beijing: China Agriculture Press.

Peng, S., Buresh, R., Huang, J., et al. (2010) Improving nitrogen fertilization in rice by site-specific N management. A review. *Agronomy for Sustainable Development*, **30**, 649–656.

Piao, S., Ciais, P., Huang, Y., et al. (2010) The impacts of climate change on water resources and agriculture in China. *Nature*, **467**, 43–51.

Price Department of National Development and Reform Commission. (2001) *Compilation of Cost and Income of Agricultural Products in China*. Beijing: China Price Press.

Roelcke, M., Schleef, K., Guo, Z., et al. (2004) Recent trends and recommendations for nitrogen fertilization in intensive agriculture in eastern China. *Pedosphere*, **14**, 449–460.

Stone, R., (2008) China plans $3.5 billion GM crops initiative. *Sciences*, **321**, 1279.

The Ministry of Water Resources of the People's Republic of China. (2009) *The Bulletin of Water Resources of China*. Beijing: China Water Power Press.

Wang, H., Liu, C., & Zhang, L. (2002) Water-saving agriculture in China: An overview. *Advances in Agronomy*, **75**, 135–171.

Wang, Y., Sheng, L., Li, K., et al. (2008) Analysis of present situation of water resources and counter measures for sustainable development in China. *Water Resources*, **19**, 10–14.

Xu, F., & Zhao, B. (2001) Development of crop yield and water use efficiency in Fengqiu county, China. *Acta Pedologica Sinica*, **38**, 491–497.

Xu, G., Hsü, K., & Peel, L. (1991) *The Agriculture of China*. Cambridge, MA: Oxford University Press.

Yan, X., Wu, P., Ling, H., et al. (2006) Plant nutriomics in China: An overview. *Annals of Botany*, **98**, 473–482.

Yang, H., Dobermann, A., Lindquist, J., et al. (2004) Hybrid-maize—A maize simulation model that combines two crop modeling approaches. *Field Crops Research*, **87**, 131–154.

Zhang, Q. (2007) Strategies for developing green super rice. *Proceedings of the National Academy of Sciences*, **104**, 16402–16409.

Zhang, X., Pei, D., Chen, S., et al. (2006) Performance of double-cropped winter wheat-summer maize under minimum irrigation in the North China Plain. *Agronomy Journal*, **98**, 1620–1626.

Zhang, F., Wang, J., Zhang, W., et al. (2008) Situation and countermeasures of nutrient utilization efficiency for major cereal crops in China. *Acta Pedologica Sinica*, **45**, 915–924.

Zhang, F., Cui, Z., Fan, M., et al. (2011) Integrated soil-crop system management: Reducing environmental risk while increasing crop productivity and improving nutrient use efficiency in China. *Journal of Environmental Quality*, **40**, 1051–1057.

Zheng, L., Zoebisch, M., Chen, G., et al. (2006) Sustainability of farmers' soil fertility management practices: A case study in the North China Plain. *Journal of Environmental Management*, **79**, 409–419.

Zwart, S., & Bastiaanssen, W. (2004) Review of measured crop water productivity values for irrigated wheat, rice, cotton and maize. *Agricultural Water Management*, **69**, 115–133.