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Review article

Long-term experiments for sustainable nutrient management in China. A review

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Abstract – China is facing one of the largest challenges of this century to continue to increase annual cereal production to about 600 Mt by 2030 to ensure food security with shrinking cropland and limited resources, while maintaining or improving soil fertility, and protecting the environment. Rich experiences in integrated and efficient utilization of different strategies of crop rotation, intercropping, and all possible nutrient resources accumulated by Chinese farmers in traditional farming systems have been gradually abandoned and nutrient management shifted to over-reliance on synthetic fertilizers. China is now the world's largest producer, consumer and importer of chemical fertilizers. Over-application of nitrogen (N) is common in intensive agricultural regions, and current N-uptake efficiency was reported to be only 28.3, 28.2 and 26.1% for rice, wheat and maize, respectively, and less than 20% in intensive agricultural regions and for fruit trees or vegetable crops. In addition to surface and groundwater pollution and greenhouse gas emissions, over-application of N fertilizers has caused significant soil acidification in major Chinese croplands, decreasing soil pH by 0.13 to 2.20. High yield as a top priority, small-scale farming, lack of temporal synchronization of nutrient supply and crop demand, lack of effective extension systems, and hand application of fertilizers by farmers are possible reasons leading to the over-application problems. There is little doubt that current nutrient management practices are not sustainable and more efficient management systems need to be developed. A review of long-term experiments conducted around the world indicated that chemical fertilizer alone is not enough to improve or maintain soil fertility at high levels and the soil acidification problem caused by over-application of synthetic N fertilizers can be reduced if more fertilizer N is applied as NO_3^- relative to ammonium- or urea-based N fertilizers. Organic fertilizers can improve soil fertility and quality, but long-term application at high rates can also lead to more nitrate leaching, and accumulation of P, if not managed well. Well-managed combination of chemical and organic fertilizers can overcome the disadvantages of applying single source of fertilizers and sustainably achieve higher crop yields, improve soil fertility, alleviate soil acidification problems, and increase nutrient-use efficiency compared with only using chemical fertilizers. Crop yield can be increased through temporal diversity using crop rotation strategies compared with continuous cropping and legume-based cropping systems can reduce carbon and nitrogen losses. Crop yield responses to N fertilization can vary significantly from year to year due to variation in weather conditions and indigenous N supply, thus the commonly adopted prescriptive approach to N management needs to be replaced by a responsive in-season management approach based on diagnosis of crop growth, N status and demand. A crop sensor-based in-season site-specific N management strategy was able to increase N-uptake efficiency by 368% over farmers' practices in the North China Plain. Combination of these well-tested nutrient management principles and practices with modern crop management technologies is needed to develop sustainable nutrient management systems in China that can precisely match field-to-field and year-to-year variability in nutrient supply and crop demand for both single crops and crop rotations to not only improve nutrient-use efficiency but also increase crop yield and protect the environment. In addition, innovative and effective extension and service-providing systems to assist farmers in adopting and applying new management systems and technologies are also crucially important for China to meet the grand challenge of food security, nutrient-use efficiency and sustainable development.

sustainable nutrient management / long-term experiment / chemical fertilizer / organic fertilizer / precision nutrient management / small-scale farming / intensive farming / precision agriculture

Contents

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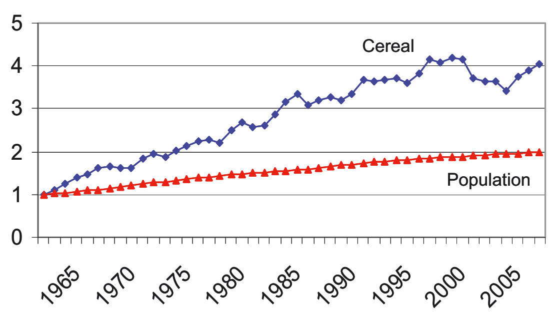

Figure 1. Relative increase in cereal production and population in China from 1961 to 2006; cereal production in 1961 was about 110 million tons and population was 673 million people (Source: FAOSTAT, 2010).

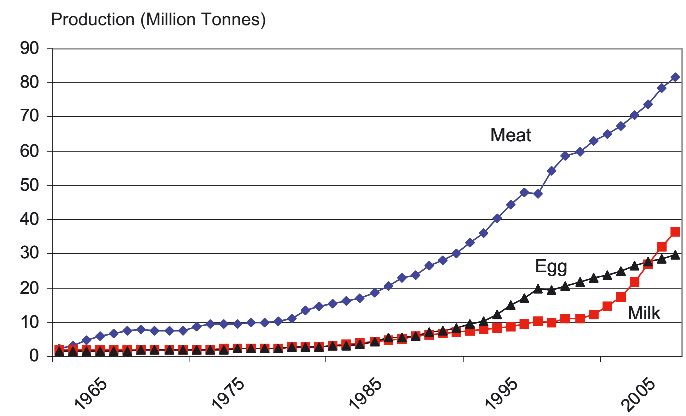

Figure 2. Production of meat, eggs and milk in China from 1961 to 2006 (million tons) (FAOSTAT, 2010).

1. INTRODUCTION

What can China learn from long-term experiments? This may sound like an odd question when one considers that agriculture in China is thousands of years old while the longest continuous agronomic experiment in the world is the Broadbalk plots in Rothamsted, England, that were begun in 1843. This question, however, is very pertinent in view of the rapid and drastic changes that have taken place in the past few decades in Chinese agriculture.

China has historically struggled to feed its large and growing population and there have been times of severe food shortages. The Great Chinese Famine, officially referred to as the Three Years of Natural Disasters, in the period between 1958 and 1961, caused more than 15 million deaths (Smil, 1999). This widespread famine brought about a major commitment of the Chinese government to increase agricultural production and achieving food security has become the single most important goal of Chinese agricultural policy for several decades.

The achievements made by China in increasing food and fiber since the time of the Great Famine have been nothing short of remarkable. The data in Figure 1 show that while the population of China has doubled since 1961, the production of cereals increased four-fold. By 1998, China's production of cereals reached the record high of 458.42 Mt, which was an increase of 418% over the 109.66 Mt produced in 1961 (FAO, 2010). This allowed the Chinese people to enjoy around 365 kg grain per person, which surpassed the world average level. Even in the recent global food crisis that has caused political unrest in over 30 countries, China has enjoyed relatively stable prices and sufficient food supply. This increase not only provided adequate supplies of grain for direct consumption, but helped to stimulate rapid gains in livestock products as shown in Figure 2. In 1961, the production of meat, milk and eggs was extremely low. Meat production was the first livestock product that began to increase, but it was slow until the late 1970s when it began to increase rather rapidly in concert with the increased grain production shown in Figure 1. Large increases in eggs did not occur until the 1990s and milk production was even slower but rapidly accelerated in the 2000s (Fig. 2).

Many factors account for the tremendous increases in agricultural production since the end of The Great Famine in

1961. In addition to irrigation, improved seeds, agricultural machinery, plastic mulch and intensification of cropping systems, application of chemical fertilizer has played a crucial role, making a 32–50% contribution to crop yield increase (Xie et al., 1998; Jin, 1998; Ma et al., 2002). China is now the world's largest producer, consumer and importer of chemical fertilizers, consuming over 1/3 of the world's chemical fertilizers and accounting for about 90% of the global fertilizer consumption increase since 1981 (Liu and Diamond, 2005). However, fertilizer- and nutrient-use efficiencies have been declining consistently in China for the past 4 decades. Nitrogen-uptake efficiency for major cereal crops in China was reported to be 28–41%, and averaged 35% in the early 1990s (Zhu, 1992). According to recent estimates based on field experiments conducted from 2001–2005 across China, current N-uptake efficiency was 28.3, 28.2 and 26.1% for rice, wheat and maize, respectively, with an average of 27.5% (Zhang et al., 2007). In intensive agricultural regions such as the North China Plain, it was even lower in farmers' fields, with average values of 18% and 15% for winter wheat and summer maize (Cui et al., 2008a, b). Zhu et al. (2005) reported that only 10% of applied N fertilizer was recovered in above-ground biomass of hot pepper, and about 52% was lost from the plant-soil system, corresponding to a loss of over 620 kg N ha^{-1}.

Mismanagement of fertilizers (especially N) and low uptake efficiencies have resulted in N losses through volatilization as ammonia (NH_3), leaching as nitrate (NO_3^-), nitrite (NO_2^-) and dissolved organic nitrogen (DON), nitrification/denitrification as dinitrogen (N_2), N_2O, and nitric oxide (NO) emissions, and has been causing a series of environmental problems (Jin, 1995; Zhang et al., 1996; Duan et al., 2000; Chen et al., 2000; Zhu and Chen, 2002; Li and Daler, 2004; Ju et al., 2009). Ammonia (NH_3) volatilization is one of the major pathways for gaseous losses of N and Xing and Zhu (2000) estimated that about 11% of the chemical N fertilizer applied was lost in this form. Xing and Yan (1999) estimated that the direct emission of N_2O from Chinese farmlands was 0.34 Mt, while 1.24 and 0.50 Mt of N, or 5 and 2%, of the total applied N fertilizers were lost through runoff and leaching, respectively (Zhu and Chen, 2002). In an investigation of groundwater contamination in North China, Zhang et al. (1996) found that nitrate concentrations in over half of the groundwater samples were higher than 50 mg L^{-1}, and the highest concentration reached 300 mg L^{-1}. In another study (Chen et al., 2005), 295 water samples were collected from wells and springs across the North China Plain (NCP) and 28 had a nitrate concentration over 45 mg NO_3^- L^{-1}. Water in 9.5% of the wells is not suitable for drinking according to the WHO standard of 50 mg NO_3^- L^{-1}. It is generally believed that due to low precipitation in the NCP and overexploitation of groundwater, the water table has been falling fast, and NO_3^- accumulated in the subsoil would not reach groundwater (Lin et al., 2008). However, Chen et al. (2005) found nitrate at a depth of 50 m in the recharge area of the NCP and as deep as 80 m near Beijing.

The future is not very optimistic! It is probably one of the largest challenges of this century for China to continue to increase annual cereal production to about 600 Mt by 2030 to ensure food security with shrinking cropland and limited resources, while maintaining or improving soil fertility, and protecting the environment. To meet the demand of an expected population of 1.6 billion in 2050, a changing diet and possible energy needs, China needs to increase grain yield by 32% by 2020 over the yield level of 2007, which requires a yield increase of 2% per year. However, total grain production has been stagnant during the past 10 years (Fan et al., 2010). The arable land area has decreased from 130 M ha in 1997 to 121.8 M ha in 2007, due to industrialization, urban construction and infrastructure development, agricultural structure adjustments, the ecological land retirement plan, and natural disasters (Wang et al., 2009). Land degradation is worsening (Zhang et al., 2007) and continues to be a threat to sustainable agricultural development. Climate change may even cause China's agricultural production to be reduced by 5–10% (Zeng et al., 2008). The demand for bioenergy may pose significant impacts on China's agriculture and environment (Yang et al., 2009). Over-fertilization has consistently been criticized (Nosengo, 2003; Zhu et al., 2005; Ju et al., 2009; Guo et al., 2010), and efficiencies need to be improved. The traditional approaches to improving nutrient-use efficiency while maintaining or slightly deceasing crop yield are not sufficient to meet China's food security challenges, and new approaches need to be developed to combine high yield crop cultivation and high efficiency nutrient management practices without endangering the environment. In order to develop sustainable nutrient management practices suitable for China in the 21st century, current practices need to be critically evaluated and lessons and experiences from around the world need to be incorporated.

Long-term field experiments are crucially important for understanding dynamic soil, nutrient, crop, management and weather processes and interactions, and provide one of the few means for evaluating sustainable agricultural management systems and better prediction of the future (Poulton, 1995; Rasmussen et al., 1998; Girma et al., 2007; Richter et al., 2007). Some trends of soil processes cannot be reliably determined with short-term studies and may only be seen over a period of time (Girma et al., 2007). Therefore, a review of the long-term field experiments around the world is both timely and warranted.

The aim of this review is to give an overview of the historical development of nutrient management in China, introduce current management problems, discuss possible reasons for over-fertilization, and then summarize some lessons from long-term field experiments that can be helpful for developing sustainable nutrient management practices in China.

2. HISTORICAL DEVELOPMENT

For over 4 000 years, Chinese farmers managed to produce modest crop yields and maintain soil fertility using traditional farming practices, emphasizing integrated and efficient utilization of different strategies of crop rotation, intercropping, all possible resources of organic manures aiming at the most complete recycling of nutrients (e.g. animal waste, human excreta, cooking ash, compost, and dredged canal sediments, etc.), and green manures (Wittwer et al., 1987; King, 1911; Ellis and Wang, 1997; Gao et al., 2006; Yang, 2006). As a major component of traditional agriculture, Chinese farmers accumulated rich experiences in collection, preparation, preservation and application of organic manures (Lin et al., 2008). A Chinese farming proverb says “Farming is a joke without manuring”. Many ancient Chinese publications mention the application of human and animal wastes to the land. For example, Han Feizi (280–233 B.C.) stated that human excreta must be applied to restore and improve soil fertility (Yang, 2006). King (1911) stated that “one of the most remarkable agricultural practices adopted by any civilized people is the centuries-long and well nigh universal conservation and utilization of all human waste in China, Korea and Japan, turning it to marvelous account in the maintenance of soil fertility and in the production of food”. However, these traditional agricultural practices could not produce enough food to meet the demand of a fast-growing population starting around 1800.

In 1949, when the People’s Republic of China was established, total grain production was only 113.78 Mt, with less than 250 kg per capita, and soil nutrients and organic matter were depleted in much of China’s agricultural land (Wang et al., 1996). A priority for the Chinese government was to increase food production and improve soil fertility using all possible sources of organic fertilizer. Even though chemical fertilizers were introduced into China over 100 years ago (Ma et al., 2002), only after the Great Famine of 1959–1961 was it realized that it was impossible to produce enough grain to meet the large food demand relying exclusively on organic fertilizers. Based on the FAOSTAT (2010) data reported in Figure 1, the amount of grain per person in 1961 was only 163 kg. As a result, large-scale chemical fertilizer production and application was introduced into Chinese agriculture starting from the mid-1960s and the Chinese government subsidized a portion of the cost so that farmers could use more of it to increase yields. The total application amount increased from 60 400 t in 1949 to 1.942 Mt in 1965, when grain production reached 194.51 Mt. Nitrogen (N) was the first nutrient that became limiting, and almost all chemical fertilizer input was N at the early stage (mostly in the form of ammonium bicarbonate, NH_4HCO_3). Its application increased from 0.5 Mt in 1961 to 5.0 Mt in 1975 and then almost linearly to 35.4 Mt in 2007 (Fan et al., 2010). Grain production was significantly increased, however, soil phosphorus (P) depletion accelerated due to higher crop uptake from widespread application of N fertilizer, and crops became responsive to P fertilizers (Shen et al., 1998). As a result, application of P fertilizers increased, from 0.7 Mt in 1965 to 2.9 Mt in 1985, and then almost linearly to 11.5 Mt in 2007 (Fan et al., 2010). The combination of N and P fertilizer application significantly increased grain production to 304.78 Mt in 1978. Little potassium (K) fertilizer was applied before the 1980s, due to lack of response, mainly because K from different organic sources was efficiently recycled back to the crop fields, including cooking ashes from burnt crop residues in farmers’ homes (Gao et al., 2006) and due to lack of sufficient mineral potash resources in China. However, due to increased crop yields and nutrient removal, K also became deficient in some regions, and combination of K fertilizers with N, or N and P fertilizers was observed to further increase crop yield (Lin et al., 2008), leading to an almost linear increase in K fertilizer consumption from 0.4 Mt in 1980 to 7.5 Mt in 2007. Total chemical fertilizer consumption increased from 38.1 Mt in 1995 to 54.4 Mt in 2007, which is about 35% of the world’s total consumption (Fan et al., 2010).

Perhaps even more important is that the contribution of organic fertilizer decreased as a source of nutrients from contributing almost 100% of nutrient input in 1949 to about 50% in 1980 and to about 35% in 2001 (Gao et al., 2006). The percentage decrease is primarily due to the tremendous increase in the use of chemical fertilizers, and not because there is less organic waste. Quite the contrary; due to the tremendous increases in grain yield, crop residues and livestock products, the total amount of available organic materials has risen significantly (Ju et al., 2005). There is little doubt that manure production will continue to increase in light of the rapid increases in meat, milk and egg production shown in Figure 2.

Although amounts of organic wastes are increasing, the use of the residues on the land is decreasing in many cases and the way they are being used is also changing. Chen et al. (2006) made a case study of Quzhou County in the NCP and reported that applications of manure seemed to be decreasing even though animal production accounted for 40% of the agricultural output compared with only 8% in the early 1980s. Farmers were apparently using the increased amounts of manure, but in a markedly different way than in the past. Traditionally, farmers mixed manure with soil to make a kind of compost (“soil manure”). Because of the economic reforms that have resulted in many farmers working in off-farm jobs, they no longer mix manure with soil but apply it directly to vegetable fields near their homes. Chemical fertilizers require much less labor to apply to the more remote land. As a result of these changes, the soil organic matter (SOM) contents of most vegetable fields and fields close to the villages have greatly increased, but have decreased on other lands. To reduce labor requirements even further, crop straw burning became a common practice in the 1990s and this resulted in even less organic material being returned to the soil. In 2008, a regulation was imposed by the Ministry of Environmental Protection and Ministry of Agriculture to prohibit the burning of straw. It is, however, unevenly enforced.

3. OVER-FERTILIZATION

3.1. Over-application of chemical fertilizers

Over-application of chemical fertilizers, especially N fertilizers, has been a common problem in intensive agricultural regions of China. Based on results from over 100 on-farm experiments across 2003–2005 in the North China Plain, mineral N application rates by farmers for winter wheat (*Triticum aestivum* L.) varied from 120–729 kg N ha^{-1}, with a mean of 325 kg N ha^{-1} (Cui et al., 2008a), and varied from 96 to 482 kg N ha^{-1}, with a mean of 263 kg N ha^{-1} for summer maize (*Zea mays* L.) (Cui et al., 2008b). 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^{-1} in 1967 to about 384 kg ha^{-1} in 1988 and 670 kg ha^{-1} in 2000 (Zhen et al., 2006). The average N application rate for rice (*Oryza sativa* L.) in China was 193 kg ha^{-1} in 2006, but rates from 150 to 250 kg ha^{-1} are common now, and can reach 300 kg ha^{-1} in some places (Roelcke et al., 2004; Peng et al., 2010). Based on over 20 000 household surveys conducted in 2000 and 2002 across 26 regions in China, the average N application rates were 215, 187 and 209 kg ha^{-1} for rice, wheat and maize, respectively (Zhang et al., 2007).

As China has shifted to a market-oriented economy, farmers now seek to maximize their economic return by planting more high value crops such as vegetables and fruit trees. As a result, the planting area for vegetables, fruits and flowers has increased 4.4 times over the past two decades (Zhang et al., 2004a). Nutrient inputs, especially N, are much higher for these cash crops than in cereal production. According to a nationwide survey, nutrient input was 60% higher in cash crops than cereal crops (Li et al., 2001). Ma (1999) reported that the average N application rate was 848 kg N ha^{-1} for apple (*Malus domestica*) orchards (n = 217) and 1700 kg ha^{-1} per crop for protected vegetable fields (plastic field 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^{-1} for Chinese cabbage (*Brassica chinensis* L.) to 882 kg N ha^{-1} for cucumber (*Cucumis sativa* L.) in open fields, and from 440 kg N ha^{-1} for cabbage (*Brassica oleracea var. capitata* L.) to 1068 kg N ha^{-1} for sweet pepper (*Capsicum annuum*) in greenhouses, based on surveys conducted from 1996–2000 in Beijing. According to another investigation conducted throughout the country, the average N application rate for high value crops (vegetables, fruit trees and flowers) was 569–2000 kg N ha^{-1} (Price Department of National Development and Reform Commission, 2001).

Over-application of chemical fertilizers mainly occurs in the more economically developed eastern coastal provinces, while in the economically backward regions such as central and western China, mineral nutrient input is much lower, and crop residues are generally not returned to the fields, but used for animal feed or cooking fuel, resulting in nutrient depletion in these regions (Gao et al., 2006). This regional imbalance problem is related to farmers' income and needs to be solved to improve crop yields in the central and western regions, and overall nutrient-use efficiencies in China. Government policy and fertilizer subsidies may need to be adjusted to encourage nutrient input in less developed and nutrient-deficient regions, and discourage over-application in favorable regions.

3.2. Nutrient imbalances

Over-application of chemical fertilizers in intensive agricultural regions has resulted in high nutrient accumulation in the soil. Nutrient budget calculation on the national scale indicated that the N surplus has increased steadily from about 2 Mt in the early 1950s to about 20 Mt in 2004 (Zhang et al., 2006). After winter wheat harvest, the average residual soil nitrate-N content was reported to be 314 and 145 kg ha^{-1} in the 0–200 cm and 200–400 cm soil profile, respectively, in the suburb of Beijing (Liu et al., 2004), and 275 kg N ha^{-1} and 213 kg N ha^{-1} in the 0–90 cm and 90–180 cm soil profile, respectively, in Shandong Province. These values were reported to be significantly higher in greenhouse vegetable fields (270–5038 and 224–3273 kg N ha^{-1} at 0–90 and 90–180 cm depth, respectively) and orchards (32-2406 and 228–2430 kg N ha^{-1} at 0–90 and 90–180 cm depth) (Ju et al., 2006).

Phosphorus (P) budgets changed from deficiency in the early 1950s (–0.31 Mt in 1952) to surplus in the 1970s (0.45 Mt in 1979), and have been increasing steadily since then, resulting in a surplus of 3.94 Mt in 2004 (Zhang et al., 2006). It has been estimated that the accumulated P surplus in China's farmland from 1980 to 2003 was 560 (with high value crops) or 392 (without high value crops) kg P ha^{-1}, and the average soil available P in 2004 was around 19 mg kg^{-1}. The application rate increased from around 2 kg P_2O_5 ha^{-1} in the 1960s to around 71 kg P_2O_5 ha^{-1} after 2000 (Cao et al., 2007). Xie and Tan (2001) estimated that about 47% of China's farmland had soil available P lower than 10 mg kg^{-1}, while soils with available P higher than 25 mg kg^{-1} were only around 10%. Soil available P in vegetable fields was significantly higher than cereal crop fields, with an average of 83.48 mg kg^{-1} (12.5–636 mg kg^{-1}). They recommended 20 mg kg^{-1} as a threshold for China's farmland.

The potassium (K) budget has consistently remained negative (Zhang et al., 2006), even though the concept of "balanced fertilization" has been promoted in China for over 20 years. Negative K balance has resulted in serious soil K depletion, which could be limiting the potential for further crop yield increase (World Bank Report, 1997). Sheldrick et al. (2003) used a nutrient audit model to calculate nutrient balances in China. They found that depletion of K increased from 2.9 Mt in 1961 to 8.3 Mt in 1997, and the depletion rates were high in all 30 provinces in 1996. Their results indicated that an average annual growth rate of K fertilizer consumption of more than 3% between 1997 and 2020 would be needed to increase annual food production by 1% and prevent further development of soil K deficiency. The surpluses of N and P and deficiency of K have been confirmed in different farming systems and regions of China by many other researchers (e.g., Xie et al., 1990; Lin et al., 2008). If the trend of K imbalance is not reversed, the potential to improve N and P fertilizer-use efficiency and further increase crop yield will be limited.

Regional imbalances should not be ignored. Soil nutrient depletion in the central and western parts of the country is still an important issue, and the situation has even deteriorated over the years (Zhang et al., 1999; Chen, 2001). Mineral nutrient input in these economically backward regions was much lower than crop requirements, and more crop residues were removed for feeding animals or cooking (Gao et al., 2006).

Compared with macronutrients, much less attention has been given to secondary and micronutrients in China. Tang (1996) reported that 46% of Chinese farmland was deficient in secondary nutrients, with Ca- and S-deficient soils being about 20%, and Mg-deficient soils being about 4%. More than 50% of soils in China have DTPA-extractable Zn contents of less than 1.0 mg kg^{-1} (Yang et al., 2007). Lin et al. (2008) estimated that about 160 M ha of farmland soil were deficient in certain micronutrients, but only 11.1% received micronutrients from chemical fertilizer application. The problem of secondary and micronutrient deficiency is expected to become more serious, and if not solved properly, will limit N-, P- and K-use efficiency and further yield improvement.

3.3. Possible reasons for over-fertilization in China

Many factors may have contributed to the over-application of fertilizers and low nutrient-use efficiencies in intensive farming systems in China, and some of them are discussed below.

3.3.1. High yield as top priority

For decades, producing high crop yields has been the top priority of agricultural production policies in China, with little attention being paid to nutrient-use efficiencies, economic returns or environmental risks. In addition to irrigation, improved seeds and pesticides, etc., chemical fertilizers have made a significant contribution to crop yield increase (Xie et al., 1998; Jin, 1998). This gave people the impression that to obtain higher yield, one needed to apply more fertilizers, leading to an over-reliance on chemical fertilizers. They were also relatively cheap in the past, and most farmers took an insurance approach to make sure that fertilizers would not be a yield-limiting factor. Crop breeding has also been focusing on developing high yield varieties, and not enough attention was paid to developing varieties that are more efficient in nutrient use. As a result, most of the cereal crop varieties in China are responsive to high nutrient inputs without having significant lodging problems; this has also encouraged high fertilizer inputs. In recent years, some efforts have been made to change this situation and develop varieties that are more efficient in using soil nutrients, which may lead to a "second green revolution" (Yan et al., 2006; Zhang, 2007).

3.3.2. Small-scale farming

Due to the large population but limited land resources, the average arable land per capita is only about 0.1 ha in China (Wang et al., 2009). This means that on average each farmer's household only has around half a hectare, which has several implications for nutrient management. Most farmers cannot earn enough income from farming alone and many young men take off-farm and part-time jobs to increase their incomes, leaving old people and women staying at home for farming. These people are less informed about farming practices than young men and are generally not motivated for more advanced farming technologies; instead, they are interested in simplified, easy and time-saving technologies. Due to small-scale farming, economic benefits derived from improved management practices generally do not translate into economic incentives for them to adopt new technologies. This may change as the fertilizer prices increased significantly in 2009.

There are about 240 million farmers' households in China, and each household not only has limited land area, but the land may also be divided into several smaller plots and scattered at different locations. These small plots generally have quite different soil and crop conditions, due to different crop types, varieties, management histories and management practices by different households, and the land allocation policies of the village collectives, which guarantee that each household is assigned some high, some medium and some low quality land in the same village. Moreover, the limited number of extension personnel and the large number of small field plots make it difficult to provide customized recommendations for each household or each plot (Lin et al., 2008). Current recommendations are made for a region (a county or a township) and do not take into account the household-to-household or field-to-field variability, which can result in either over- or under-application of agricultural inputs (e.g., fertilizers), and result in low resource efficiencies or crop yields.

In addition, the current land tenure system in place since the early 1980s, the Household Responsibility System, has a negative impact on sustainable nutrient management practices. The land is owned by the government or the collectives, and the farmer only has the right to manage it. He cannot buy, sell or inherit the land (Gao et al., 2006), although new policies adopted in late 2008 now allow the farmer to rent his land to other farmers. Many farmers thus feel they are temporary caretakers and lack the interest in investment for soil fertility improvement; even though many of them have long-term contracts (Tso, 2004). Therefore, shortsighted decision-making and irresponsible use of land resources can be a problem (Gao et al., 2006).

3.3.3. Lack of temporal synchronization

Large amounts of N fertilizer are generally applied preplanting or at planting by many farmers, while the peak of crop N uptake is later in the growing season. Several reasons may contribute to this phenomenon. One reason is that most farmers have a low education level, and do not have a good understanding of the dynamics of N and patterns of crop N demand. Another reason is the increasing opportunity cost (off-farm income possibilities) for farmers. Many young educated farmers have temporary jobs in the cities, and they do not have time to come back for in-season N application.

3.3.4. Lack of effective extension systems

Current extension services in China are offered by county-level "Agricultural Technical Extension Centers" and township-level stations, while most villages do not have any extension personnel. Most farmers cannot get customized advice for crop and nutrient management, and they mainly rely on their peers for new technologies. The extension system generally takes a top-down approach, deciding what technologies

Figure 3. A farmer is applying topdressing N fertilizer by hand for winter wheat in Huimin County, Shandong Province, China. It is difficult for farmers to apply the right rate and amount by hand, and this can easily lead to over-application (Photo Courtesy: Fei Li).

should be transferred at the central, provincial or county level, without sufficient involvement of local farmers. There is no formal certification system for evaluating the qualification of extension personnel, and sometimes one can meet an extension person with an education background other than agriculture. Many extension agencies not only offer fertilizer recommendations, but also sell agrochemicals, resulting in possible conflict of interest. There are also many uncertified salesmen selling agrochemicals, and there are many cases of fake products, which have lower nutrient contents than values indicated on the bags. This has also caused some farmers to apply more than recommended, in case their fertilizers are fake. It should also be pointed out that education, research and extension are not well integrated in China, and there are barriers and gaps of knowledge and technology transfer between research institutions and extension agencies. To overcome these barriers, the China Agricultural University in Beijing set up the "Agricultural Extension Professor System" and "Professional Master Degree Program for Agricultural Extension" in 2006, and many other universities have followed these actions.

3.3.5. Hand application of fertilizers

In China, most farmers apply fertilizers by hand (Fig. 3), due to lack of proper fertilizer application machinery or inability to afford such systems by small-scale farmers. Generally, no farmers will carry a balance to weigh fertilizers and it is difficult for them to apply the right rate and amount by hand, even when they know how much they should apply. To ensure that enough fertilizers be applied and crop yield will not be limited, they usually apply more than necessary, which undoubtedly leads to widespread over-application. Suitable fertilizer application machines or practical containers for measuring fertilizers in the field should be developed for small-scale farming; otherwise, improving nutrient management will remain a slogan.

4. WHAT CAN WE LEARN FROM LONG-TERM EXPERIMENTS?

During the past two centuries, a large number of agricultural experiments were initiated around the world (Rasmussen et al., 1998), including the Broakbalk plots initiated by Lawes and Gilbert in 1843 in Rothamsted, England (Moss et al., 2004), the Morrow Plots established in 1876 on the campus of the University of Illinois in Urbana, Illinois (Khan et al., 2007), Sanborn Field started in 1888 on the campus of the University of Missouri-Columbia, MO (Buyanovsky and Wagner, 1998), the Magruder Plot initiated by Alexander C. Magruder in 1892 just off the Oklahoma State University campus in Stillwater, OK (Girma et al., 2007), the Eternal Rye trial of Martin-Luther-University established by Julius Kühn in 1878 in Halle (Saale), Germany (Merbach et al., 2000), the Askov Long-Term Experiments on Animal Manure and Mineral Fertilizers in Denmark started in 1894 (Christensen, 1997), the Bad Lauchstadt "Static Experiment" established in 1902 in Germany (Marhan and Scheu, 2005) and the Longerenong Rotation 1(LR1) experiment established in 1916 near Horsham in Southeastern Australia (Norton et al., 2010). There are several other field experiments with over 50 years of duration in Australia, Poland, Canada and South Africa (Rasmussen et al., 1998; Nel et al., 1996). During the past few decades, many new long-term experiments have been started in developing countries, such as India and China. The Long-Term Continuous Cropping Experiment (LTCCE) initiated in the 1960s by the International Rice Research Institute (IRRI) is the best known rice experiment, featuring intensive rice management systems (Dobermann et al., 2000; Richter et al., 2007). Results from these long-term experiments may help answer some of the important questions concerning sustainable nutrient management in China.

4.1. Long-term over-application of synthetic N fertilizers may jeopardize soil fertility and agricultural sustainability

Nutrient management has played a crucial role in the achievement of Chinese agriculture during the past few decades; however, its sustainability has long been questioned. A major concern is that over-reliance on chemical fertilizer, especially over-application of N in intensive farming systems, may deteriorate soil fertility and quality, and jeopardize crop productivity and long-term sustainability, in addition to negative environmental and ecological consequences.

4.1.1. Soil carbon and nitrogen

Soil OM is the most important indicator of soil fertility, quality and productivity, and is usually estimated by determining SOC (Rasmussen et al., 1998). It is generally believed that N application increases residues, including roots, returned to the soil, and as a result, can increase SOM content and C sequestration (Paustian et al., 1997; Lu et al., 2009). Several recent studies based on a review of long-term experiments conducted across China, as well as modeling, satellite remote sensing, atmospheric inversions or a combination of different methods all revealed that China has become a net C sink, and topsoil OM content has increased in most croplands of mainland China, except for decreases in the Northeast and Southwest regions (Huang and Sun, 2006; Piao et al., 2009; Yu et al., 2009). They attributed the increase in SOC to increased application of N and other fertilizers, together with increased residue return, and partial adoption of reduced or no-till practices as the contributing factors. After reviewing long-term field experiments in China, Lu et al. (2009) found linear relationships between soil C sequestration and amount of N fertilizer applied and straw returned.

Contrary to this general belief, Khan et al. (2007) analyzed SOC data from the Morrow Plots and found a net decline in soil C after 40–50 years of chemical fertilizer application exceeding grain N removal by 60–190% and despite large amounts of crop residue returned. The loss was more intensive for the subsurface soil layer or the whole soil profile (0–46 cm) than the surface soil or plow layer. The high NPK (HNPK) treatment, with higher N rates than the NPK treatment, resulted in more serious loss of SOC. Their finding is in agreement with many other long-term studies conducted under different tillage systems across the US, with different crops and cropping systems, as listed by the authors. In response to long-term studies that found N fertilizers increased SOC, Khan et al. (2007) pointed out several possible reasons. Some of these studies do not have baseline data for comparison but were compared with unfertilized control. The results can also be misleading if the experiments were confounded by previous manure application. Some studies only evaluated the surface soil layer, without investigating the subsurface layer. Some of the studies are not long enough for SOC change detection. Long-term application of ammonium fertilizers can acidify soil, which can impede soil C decomposition, if no lime was applied to correct the problem. Under this situation, crop yield can be negatively affected.

Mulvaney et al. (2009) hypothesized that SOC loss can also lead to soil organic N loss, because microbial C and N cycling is coupled. These two elements in soils are dominantly in organic forms, and their mineralization is closely correlated. Using data from the same long-term experiment (Morrow Plots) as Khan et al. (2007), they confirmed this hypothesis. They found that soil N declined in all the 6 subplots evaluated and the loss was more intensive for subsurface soil layers (15–50 cm and 30–46 cm) than for the plow layer, and more intensive in HNPK (with a high N rate) plots than in NPK plots. They also reviewed and compiled a large number of published results from long-term experiments conducted around the world, and reached a similar conclusion.

Why does N fertilization decrease SOC and N? It is believed that fertilizer N can enhance the activities of heterotrophic soil microorganisms that use C derived from crop residues or SOM and thus stimulate decomposition (Mack et al., 2004; Khan et al., 2007). With more N addition, the C: N ratio will be decreased, and this will cause a shift from fungal-dominated to bacterial-dominated microbial communities, which will result in faster decomposition of SOC (Moore et al., 2003). An equilibrium exists between a labile organic N pool produced by immobilization of mineral N during residue decomposition with a larger and more stable pool associated with humus, and this equilibrium will shift toward immobilization with a higher input C:N ratio, but toward mineralization or decomposition with a lower input C:N ratio (Mulvaney, 2009). More decomposition will result in more dissolved organic C and N, which can be lost through leaching (Mack et al., 2004; van Kessel et al., 2009), C loss via CO_2 (Cleveland and Townsend, 2006), or N loss from the soil system through crop uptake, denitrification or leaching (Mulvaney, 2009). For example, Fierer et al. (2003) investigated the influence of soil moisture, temperature, and nutrient (N and P) levels on the mineralization of soil C stored in the surface (0–25 cm) and subsurface (>25 cm) soil layers, and they found the addition of either N or P nutrients increased CO_2 production by as much as 450% compared with control in the subsurface soil layer, while the effect was negligible at the surface soil layer.

Several scientists, however, interpreted the Morrow Plot results differently (Reid, 2008; Powlson et al., 2010). Powlson et al. (2010) pointed out that the observed decline in soil C and N in the Morrow plots was probably still affected by the conversion from natural grassland to cropland started from 1876, and also due to the cessation of 62 years of organic manure application in 1967, when the high NPK treatment started. This is supported by the results from the long-term Hoosfield Barley Experiment in Rothamsted that soil N and C concentrations continued to decline slowly even after more than 100 years of manure application stopped (Johnston et al., 2009). Nevertheless, Raid (2008) agreed that the decline in SOC concentration is associated with modern annual crop management systems relying on synthetic fertilizers, and the decline cannot be mitigated by increased residue inputs resulting from heavy N applications.

Based on the above results, the apparent increase in SOC in certain agricultural regions in China is probably still an effect of the centuries-old manuring practices carried out in traditional Chinese agriculture (as mentioned in Sect. 2 of this paper), but also thereafter. From the late 1960s up to the early 1980s, when self-reliance was stressed and mineral fertilizers were not readily available or of poor quality (e.g. NH_4HCO_3), the use of animal manure, green manure, canal sediments for making waterlogged compost (*Cao Tang Ni)* in rice production, aquatic plants gathered from canals, etc., was very widespread. Very great amounts (several tons of farm manure per ha) of organic matter which had been stabilized via composting (as waterlogged compost or "soil manure") were returned to the fields as basal fertilizer up to 3 times a year. This led to a strong build-up of SOM. In certain areas it even led to man-made soil horizons (NW China) or the raising of the field level above the canal and river level (Yangtse-Delta Region), similar to polders in Holland (Roelcke, personal communication). It is therefore very important to replenish the SOC pool with farmyard manure (FYM) or similar organic fertilizers, as had been done by earlier long-standing manuring practices. The abandonment of the most labor-intensive manuring practices since the late 1980s, further aggravated by the increase in crop straw burning since the 1990s, is only beginning to show its negative effects. The increased amount of crop residues (which are furthermore only seldom returned to the field nowadays) and root exudates resulting from yield increases due to higher mineral fertilization alone will never lead to higher SOC contents in Chinese soils if taken on their own!

Significant soil organic C and N loss in large areas of China may have already occurred, because both under- and over-application of N fertilizer can result in SOC and N loss, and under- as well as over-application of N fertilizers each affected 1/3 of Chinese farmers, based on a recent survey (Fan et al., 2010). This may also help explain the crop yield stagnation during the past decade in China. It is unfortunate that almost all researchers in China only investigated the surface soil layer (0–17 or 20 cm) in the long-term studies, yet many researchers have emphasized the need to sample subsurface soils (Baker et al., 2007; Khan et al., 2007; Mulvaney et al., 2009). This suggestion should be adopted in future investigations. On the other hand, China's situation may be different, because SOC in most Chinese soils is already very low, while SOC in most of the long-term experiments in North America and Europe is much higher. This is also reflected in China's regional soil C change. The Northeast region of China, especially in Heilongjiang, has a shorter cultivation history, and SOC is much higher than in other regions, and SOC has been decreasing, while the opposite trend has been observed in many other regions of China (Huang and Sun, 2006; Piao et al., 2009; Yu et al., 2009). Anyway, the message from the long-term experiments is clear: N application needs to match crop demand better and nutrient management needs to be balanced, in order to maximize crop productivity and economic profitability without losing long-term sustainability.

4.1.2. Soil acidification

Long-term application of ammonium- or urea-based N fertilizers in crop production can result in soil acidification and changes in soil chemical properties, which can reduce biodiversity, retard nutrient cycling, and release potential toxic metals into water and plants, leading to soil degradation, environmental pollution and reduced crop yield (Bolan et al., 1991; Bouman et al., 1995; Barak et al., 1997; Goulding and Blake, 1998; Malhi et al., 1998; Rasmussen et al., 1998). Liming will be needed to correct the problem, which will increase the economic cost of farming. In addition to potential soil acidification effects, NH_4^+-containing fertilizer and urea may result in nitrate leaching as well, because ammonium-based N fertilizers can be nitrified after application to soil. When urea is applied at the soil surface, more than 50% of it can be lost through ammonia volatilization (Sommer et al., 2004).

Over-application of N fertilizers has already caused significant soil acidification in major Chinese croplands (Guo et al., 2010). Based on a national survey conducted in the early 1980s and almost all published data between 2000 and 2008, they found that topsoil pH declined by on average 0.13 to 0.80 for different soil groups across China, except the highest pH soils. According to 154 paired data comparisons, it was found that pH in these topsoils declined by on average 0.5 ($P < 0.001$). Data from 10 long-term monitoring field sites indicated that soil pH decreased by 0.45 to 2.20 (Guo et al., 2010). Significant soil acidification has been found to drastically decrease crop yield in several treatments of a long-term experiment conducted in Hunan Province, China (Zhao et al., 2010). However, the correction would theoretically require 1.5 to 2.5 tons of $CaCO_3$ ha^{-1} yr^{-1} to counteract the acidity generated in the intensive cropping systems receiving high rates of N fertilizer application, and ten times this amount for greenhouse vegetable systems, which is a daunting task (Guo et al., 2010).

The negative impact of N fertilizer application on soil acidity, SOC and N loss may be reduced if more fertilizer N is applied as NO_3^- relative to fertilizer-derived NH_4^+-N (Mulvaney et al., 2009). In the study of Dyke et al. (1983), $CaNH_4(NO_3)_3$ was used and the net N loss from soil decreased from 10 kg ha^{-1} yr^{-1} at a 48 kg N ha^{-1} yr^{-1} N application rate to a net soil N gain of 10 kg ha^{-1} yr^{-1} at a 192 kg N ha^{-1} yr^{-1} N application rate, although N loss from fertilizer and total N loss increased with N application rate. However, when urea was used (Kundu and Samui, 2000), a net soil N gain of 5 kg ha^{-1} yr^{-1} at a 100 kg ha^{-1} yr^{-1} N rate changed to a net soil N loss of 17 kg ha^{-1} yr^{-1} at a 200 kg ha^{-1} yr^{-1} N rate. Persson and Kirchmann (1994) found in a long-term experiment started in 1956 in Sweden that straw return + N fertilizer in the form of $Ca(NO_3)_2$ increased more soil C and N than green manure in the topsoil layer. It would be more desirable if they had also examined subsurface soil. The use of NO_3^-, however, may result in more leaching if it is not managed carefully.

A combination of different types of fertilizers will be more desirable, using urea- and ammonia-based N fertilizers as preplant or basal application, while using NO_3^--based fertilizers for topdressing or side dressing. Soil type differences also need to be considered in deciding the type of N fertilizer to be used.

4.2. Long-term application of organic fertilizers may also have disadvantages

The benefits of long-term application of organic fertilizers such as manure have long been recognized, and confirmed by long-term experiments, including higher organic matter content, hydraulic conductivity, porosity and aggregate stability, lower bulk density and increased soil biological activity than soils only receiving inorganic fertilizers, and more complete supply of nutrients (Edmeades, 2003; Diacono and Montemurro, 2010). In the Broadbalk plots, manure application increased soil bacteria and actinomycetes, without having any effect on soil fungi.

However, long-term application of organic manures can also have several negative effects. Many long-term experiments indicated that soils with cattle manure application had increased levels of OM, P, K, Ca and Mg in the surface soil, and increased levels of nitrate-nitrogen (NO_3^-–N), Ca and Mg in the subsoil, as compared with soils receiving inorganic fertilizers (Edmeades, 2003). Goulding et al. (2000) observed larger N leaching loss from the plots treated with FYM in the Broadbalk experiment. Fall application is part of the reason, because N mineralized in fall and early winter was not used by the crops, and subject to leaching. Another reason is that after over 150 years of application, the SOM had more than doubled, and the amount of N from mineralization was very large. The increased porosity in manured soils can also facilitate NO_3 leaching. Stewart et al. (2000) discussed the ratio of N and P in manure compared with that in major crops. They stated that corn and wheat require approximately five times as much N as P, and that the ratio of N to P in beef cattle manure is only about 2.5 to 1. Thus, if sufficient manure is added to supply N needs, there is often a high accumulation of P. Even when manure supplied only part of the nutrients in the 15-year China study by Zhang et al. (2009a), there was a very high build-up of available P in the soil at the end of the study. Enriched P in the soil may be lost through runoff, or leached in soils with low P retention or in situations of organic P leaching, thus leading to water pollution (Edmeades, 2003). Therefore, P levels in the soil need to be monitored not only to indicate when available P is insufficient, but also when it is present in excessive amounts.

4.3. Combination of inorganic and organic fertilizers leads to more sustainable nutrient management systems

After reviewing 14 long-term experiments conducted in North America and Europe that all have yield data for over 20 years, Edmeades (2003) indicated that balanced chemical fertilizer application and manure application at equivalent nutrient rates can achieve similar crop yield. Only after a very large amount of manure has been applied for a very long time, which may result in large differences in SOC, can any additional benefit of organic manure application on yield be observed, as in the Broadbalk experiment. At a specific site, manure treatment can have higher, similar or lower yield compared with chemical fertilizer treatment, depending on the previous soil organic C pool, soil management, soil type, type, rate and frequency of chemical and organic fertilizer application, etc. (Edmeades, 2003; Lal, 2006; Diacono and Montemurro, 2010).

Sufficient evidence indicates that the combined application of NPK fertilizers and organic fertilizers (NPK+OF) can generally achieve higher crop yields than any of them applied alone (Poulton, 1995; Greenland, 1997; Manna et al., 2007; Hati et al., 2007; Bhattacharyya et al., 2008; Xu et al., 2008; Pan et al., 2009; Zhang et al., 2009a, b, c; Diacono and Montemurro, 2010; Zhao et al., 2010). A long-term field experiment from 1973 to 2004 conducted in India indicated a significant downward trend in yield of soybean for both the control treatment and the NPK treatment compared with a statistically significant upward trend with time for the NPK + FYM treatment (Bhattacharyya et al., 2008). Similar, but not statistically significant, trends were observed for wheat yields. They concluded that the different combinations of mineral N, P and K fertilizers could not achieve yield sustainability under soybean-wheat rotation. The higher soybean and wheat yields obtained with the FYM + NPK treatment were possibly caused by other benefits of organic matter exceeding N, P and K supply, such as improvements in microbial activities, better supply of macro- and micronutrients such as S, Zn, C and B, which are not supplied by inorganic fertilizers, and lower losses of nutrients from the soil. They also stated that improved soil physical properties on the FYM-treated plots were observed and may have contributed to the improvement in crop yields. In another 28-year long-term experiment also conducted in India, Hati et al. (2007) found that the combined application of NPK and FYM not only produced significantly higher soybean and wheat yields than NPK treatment, but also increased SOC by 56.3% compared with the initial SOC value at the beginning of the experiment. The treatment increased soil electrical conductivity, SOC content, aggregation, water retention, microporosity and available water capacity, but decreased soil bulk density over all other treatments. In a long-term maize-wheat-cowpea experiment started in 1971 in India, Kanchikerimath and Singh (2001) found that the inorganic fertilizer (NPK) increased crop yield, SOC, total N, mineralizable C and N, microbial biomass C and N, and dehydrogenase, urease and alkaline phosphatase activities, while manure applied together with inorganic fertilizer increased these parameters more strongly. Earthworm activity is also generally increased when farmyard manure is added to soil. Cao et al. (2004) studied the effect of various combinations of chemical fertilizer, crop residues and organic fertilizers on earthworm populations in a high production agro-ecosystem in North China. The earthworm density of the treatments had the following ascending trend: chemical fertilizer < chemical fertilizer + wheat straw < chemical fertilizer + wheat straw + corn stover < chemical fertilizer + wheat straw + corn stover + organic fertilizer. The earthworm biomass decreased with application of chemical fertilizer without organic input or only with added wheat straw. The trend became greater with increasing time. The authors concluded that their results implied that to maintain good soil fertility, organic material input is critical. In the Bad Lauchstadt long-term experiment in Germany, Marhan and Scheu (2005) found that FYM and NPK+FYM increased earthworm biomass by 19.7 and 42.8%, respectively, while the NPK treatment decreased earthworm biomass by 9.4%. They concluded that the application of NPK fertilizers alone cannot sustain the earthworms, but NPK+FYM can do so due to increasing the utilizable SOM pool. Although the reasons were not fully understood, the results clearly showed that the highest and most sustainable yields were only reached when FYM was added in addition to inorganic fertilizers.

A 15-year study in Qiyang, Hunan Province, in southern China was recently summarized (Zhang et al., 2009a) and the results are similar to those of other countries reported above. The addition of N, P and K applied alone or in combination with one another generally showed a good response but only until another element became limiting. For example, the addition of N alone gave a significant response the first two or three years of the study, and N and P added simultaneously

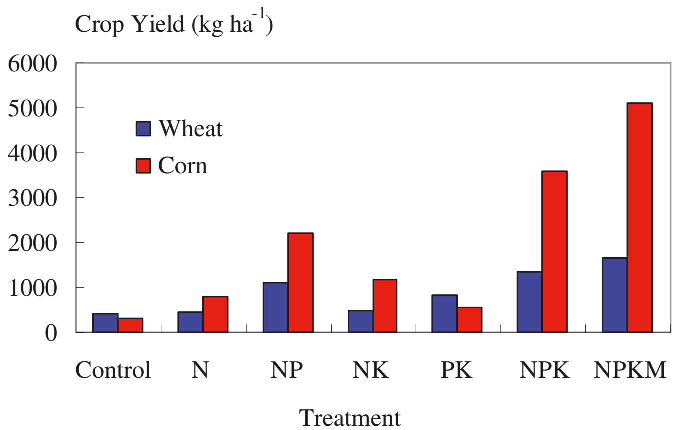

Figure 4. Average yield of wheat and corn grain (kg ha^{-1}) for a 15-yr study in Qiyang, Hunan, China. The NPKM treatment had the highest wheat and corn yield, followed by the NPK treatment, indicating the importance of combination of organic and inorganic fertilizers and balanced nutrient application (Data from Zhang et al., 2009a).

increased the yield of both wheat and corn about five-fold during the same time period. However, there was a momentous decrease in yield of both crops in succeeding years. The addition of K along with N and P improved the yields in some years, but yield also decreased after some time, while high yields were sustainable over the duration of the study only when FYM was added along with the chemical fertilizers. The average yields of wheat and corn for the 15-year period for each of the treatments are shown in Figure 4. NPK and NPKM consistently had higher yields than the other treatments, in which one or more nutrients were lacking. Corn yield increased over time in NPKM.

Zhang et al. (2009b) summarized the results of nine long-term experiments conducted across different agro-ecological regions of China. They found that compared with NPK, the combined application of NPK and FYM resulted in a higher increase in SOC in the maize and wheat-maize systems than in rice and rice-wheat systems, and in increased crop yields during the last few years of the experiment for the maize and wheat-maize systems, but during the initial years in the rice and rice-wheat systems. Zhang et al. (2009c) found that long-term application of pig manure resulted in continuous increase in SOC and total soil N in a wheat-corn rotation system, and that the highest rate of NPKM increased SOC the most, while the application of only inorganic fertilizers had little influence on SOC, but decreased total soil N.

Raun et al. (1993) found that when environmental conditions were not good (environmental mean yield was <2 Mg ha^{-1}), the NPK-treated plots had better yield than the cattle manure treatment, while when the growing conditions were optimal, cattle manure treatment had a better performance. Thus, the combination of both types of fertilizers produced a more stable yield.

Combined application can alleviate the soil acidification effect of ammonia-based or urea fertilizer, because manure contains abundant basic cations such as Ca and Mg. In the Magruder Plot, Zhang (1998) found that the pH in the cattle manure application plots was at the optimum level of 6.20, compared with 5.1 for the NPK treatment.

Since manure application based on crop N need will result in P enrichment, it has been suggested that manure application should be based on crop P need, and then use of N fertilizer to supplement N need. This also indicates the advantage of and need for combined application.

In addition to higher crop yield, Pan et al. (2009) also found combined application of chemical fertilizer and pig manure (CFM) or chemical fertilizer plus rice straw return (CFS) increased N partial factor productivity (PFP, crop yield divided by N input) by an average of 27 and 54%, respectively, over chemical fertilizer alone. This increase in N-use efficiency can be translated into potential savings of ~ 2 Mt yr^{-1} inorganic N fertilizer in rice production in China, which may offset 1.7–3.5 Mt C emissions per year.

Based on the above review, it is fair to conclude that combination of organic and inorganic fertilizers is a better practice than applying organic or inorganic fertilizers alone, although Zhao et al. (2010) made a good point by pointing out the fact that the manure + NPK treatment often had the highest inputs of nutrients and the highest yield should be expected. They called for better design of experiments to test different rates of inorganic fertilizers with and without manure to clarify unique contributions of manure that cannot be reproduced by using additional inorganic fertilizers. However, they do recognize the potential wider and long-term benefits of increased SOM.

A common thread illustrated by these long-term studies presented above is that continuous cropping removes nutrients from the soil and that eventually inputs are required to maintain sustainability. Needless to say, yields can be sustained at a low level much longer than at a high level.

Atmospheric N deposition may have played an important role in sustaining crop yields in control plots receiving no N application in the long-term field experiments, especially in intensive Chinese agricultural regions. In a recent study, He et al. (2010) reported 99 to 117 kg N ha^{-1} yr^{-1} total N deposition in winter wheat-summer maize cropping systems of Dongbeiwang in a Beijing suburb and Quzhou in Hebei Province. These high levels of atmospheric N deposition must be taken into account when calculating N budgets and developing N management strategies.

It is also apparent from the studies presented that N is usually the first nutrient that becomes limiting and the addition of N fertilizer will generally restore the yield level, at least for a while. Then, P often becomes the next limiting nutrient, followed by K, and sometimes by S or some other essential nutrients. In most long-term studies, the highest yields could only be obtained by a combination of farmyard manure and chemical fertilizers. The reasons are not always apparent. In some cases, it may be that some micronutrients are deficient. In other cases, it may be the beneficial effects from improved soil physical properties. Biological activity is also positively affected by organic amendments. Bhattacharyya et al. (2008) showed a marked increase in soil microbial biomass and enzyme activity when farmyard manure was added. Long-term application of high rate compost can increase microbial biomass carbon in the soil by up to 100%, and sludge application can increase enzymatic activity by 30% (Diacono and Montemurro, 2009).

In fact, the benefits of integrated application of both inorganic and organic fertilizers have long been recognized by Chinese scientists and farmers. However, there are several obstacles or challenges to an increase in the use of organic amendments in agriculture. The low economic return of farming and the rising opportunity cost of rural labor have been suggested as the most important reasons for decreasing use of the more labor-intensive organic manure (Gao et al., 2006). Another challenge is the delinking or decoupling of livestock and crop production, due to the development of large industrialized confined intensive livestock production (Naylor et al., 2005). Accompanying rapid development of China's livestock industry during the past few decades, the problem of organic manure management is increasingly becoming a concern. Traditionally, livestock production had two systems: grazing mainly in North and Northwest China and mixed crop and livestock farming, both mainly using local feed resources (Li et al., 2008). During the past two decades, industrial livestock systems in the form of large-scale, intensive operations have been developing very fast. They are mainly located near large cities, especially in the eastern coastal areas, but also extending away into inland areas (Li et al., 2008; Li, 2009). Even though traditional operations are still the majority in number, accounting for 93.77% of the total farms, the 6.23% intensive operation farms produced about 56% of the total livestock products in 2003 (Li et al., 2009), with a further increasing trend. These large intensive operations generate a large amount of organic wastes and air and water pollution (Li et al., 2008). Because it is not practical or economical to transport the low-density manure on a large scale over long distances, excessive amounts of manure are applied to fields in the vicinity of intensive livestock productions, which can cause over-accumulation of nutrients in the soils (Gao et al., 2006), whereas many crop fields needing the manure to build up soil fertility do not have easy access to them. Therefore, a recoupling of livestock and crop production is definitely needed, both on a local and regional scale. Another challenge is the difficulty of accurately predicting nutrient mineralization from different types of manures in different cropping environments, leading to either over- or under-application of inorganic fertilizers (Zhao et al., 2010).

4.4. Increasing temporal diversity for high yield and sustainability

Rothamsted Research (2006) summarized the yields of wheat from 1852 to 1999 for selected treatments on the Broadbalk plots (Fig. 5). It is noteworthy that the yield of wheat was sustained for over 140 years when no manure or fertilizer was added, but at a very low level. There was little or no benefit from improved cultivars, weed control or other technological improvements. Application of either NPK fertilizers or FYM significantly increased crop yield, however, when rotations were introduced; much higher yield was achieved with either NPK fertilizers or FYM+N. This yield increase was believed to be due to minimized soilborne pests and diseases, especially take all (Gaeumannomyces graminis var. tritici).

Norton et al. (2010) recently summarized the results of the Longerenong Rotation 1 (LR1) experiment in Australia, and found the rotation of wheat/barley/peas (WBP) was most productive and profitable among 7 different wheat-based cropping systems evaluated, producing 2.5 times the energy equivalence of the continuous wheat system. They believe that each phase in a crop rotation can provide disease breaks, opportunity for alternative weed control strategies, and/or improve soil conditions to support and enhance the following crops, and thus crop rotation is fundamental for sustainable production systems.

In addition to inorganic and organic fertilizers, biological N fixation is another important N source that should not be neglected. Drinkwater et al. (1998) evaluated three different cropping systems in a 15-year study: a conventional system involving maize-soybean rotation with mineral N fertilizer being applied before maize was planted, a legume-based system simulating a beef operation in which crop biomass was used as feed for cattle and manure was used as a N resource (MNR), and a legume-based system involving several legume crops, small grain crops and maize (LEG system). They found that these three systems did not differ in maize yield. After 15 years, soil C did not change significantly for the conventional system, while soil N change was negative. Both the MNR and LEG systems increased soil C and N, suggesting the benefits of using low C-to-N residues and increasing temporal diversity for maintaining soil fertility.

4.5. Temporal variability in crop responses to nitrogen fertilizer application needs to be considered for improving nitrogen-use efficiency

Current N recommendations are mainly based on multi-site-year regional N response experiments, and an optimum N rate is usually determined and recommended for a region. Spatial variability in soil nutrients and responses to fertilization and the need for site-specific nutrient management have been recognized in China (Jin and Jiang, 2002; Liu et al., 2009; Peng et al., 2010); however, year-to-year variability in crop yield, its responses to N fertilizer, and thus optimum N rates have not received enough attention. In the analysis of long-term rain-fed winter wheat N rate experiments conducted in Oklahoma, USA and irrigated corn N rate experiments conducted in Nebraska, USA, Johnson and Raun (2003) found that crop yield responses to N application in the same field could vary significantly from year to year. From Figure 6, we can see in some years, there was no significant difference between wheat yield receiving 0 and 112 kg N ha^{-1}, but in some years, the difference could be more than two-fold. Miao et al. (2006) used a crop growth model to estimate the economically optimum N rate (EONR) over 15 years and found EONR in the same field could vary from 70 to 250 kg ha^{-1}, also demonstrating the need to manage year-to-year variability in N responses. Johnson and Raun (2003) proposed a response index (RI) for evaluating crop response to N fertilizer, and it is calculated by dividing the maximum yield with N application by the yield

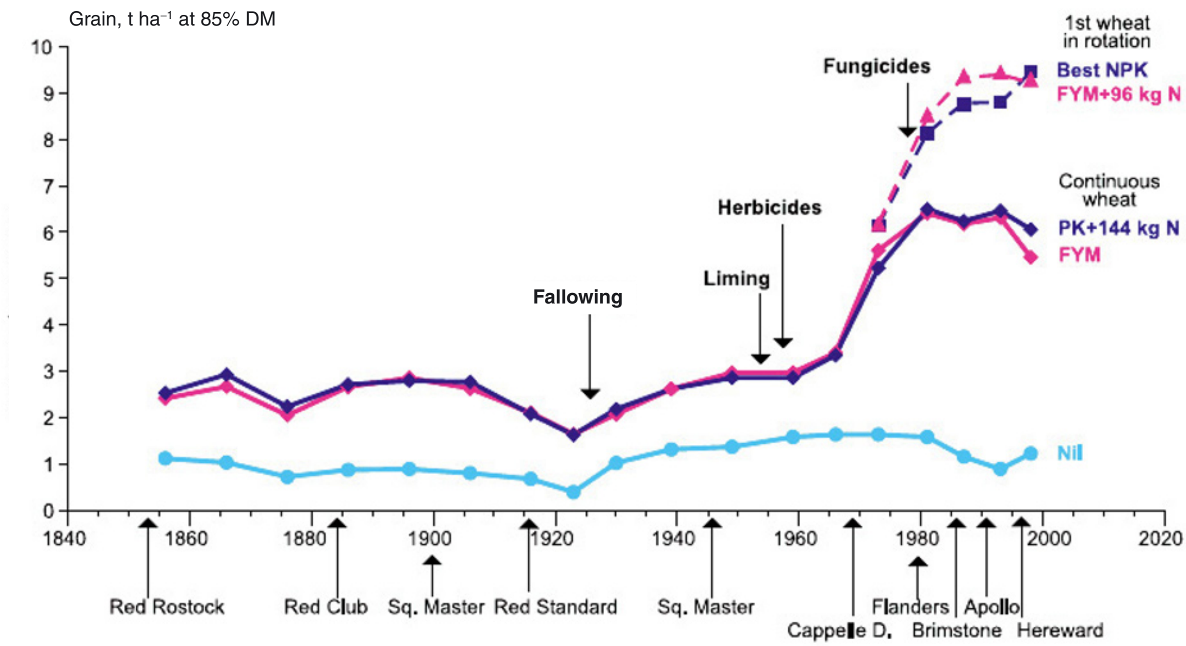

Figure 5. Mean yields of wheat grain on Broadbalk plots from 1852 to 1999 treated with NPK fertilizers, farmyard manure (FYM), FYM+N or no fertilizers, showing the effects of changing cultivar and the introduction of weed control, fungicides and crop rotation (Rothamsted Research, 2006).

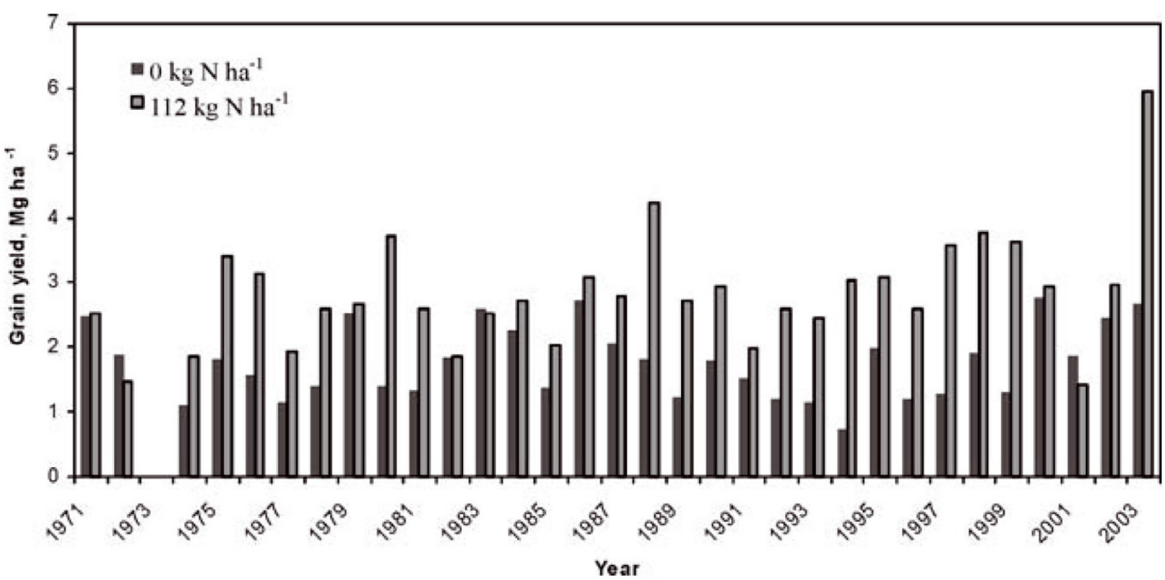

Figure 6. Average winter wheat grain yield from 1971 to 2003 from treatments receiving 112 kg N ha^{-1} annually and no fertilizer N (0 kg N ha^{-1}), long-term experiment #502, Lahoma, OK. P and K applied each year to both treatments at rates of 20 and 56 kg ha^{-1}, respectively (From Raun et al., 2005).

without N application. Nitrogen-use efficiency was found to increase with RI. A crop canopy sensor-based in-season N management algorithm was developed and was able to increase N-use efficiency by 15% in winter wheat (Raun et al., 2002, 2005). Shanahan et al. (2008) stressed the need for responsive in-season N management and described several different approaches. It is widely accepted that we need to match nutrient supply with crop demand better in both space and time to increase nutrient-use efficiency, and such precision agriculture approaches are required for both large- and small-scale farming (Matson et al., 1997; Cassman, 1999; Cassman et al., 2002; Tilman et al., 2002).

Large year-to-year variability in crop yield has also been observed in long-term experiments in China (Zhao et al., 2010) and in-season N management strategies based on soil N_{min} tests have been evaluated (Cui et al., 2008a, b). Recently, Li et al. (2009) compared two in-season N management strategies for winter wheat in the NCP: one uses a soil N_{min} test to determine soil N supply at the F6 stage, and then estimates the N topdressing rate; another strategy uses an optical canopy sensor to estimate crop N demand before topdressing, and then determines the N application rate following Raun et al. (2002). The soil Nmin-based and crop sensor-based in-season site-specific management strategies show a drastically increased N-uptake efficiency from 13.1% with the farmers' practice to 51% and 61.3%, respectively, without significant difference in grain yield. Therefore, precision N management has a good potential to significantly improve N-use efficiency in China, because it considers both spatial and temporal variability in soil N supply and crop N demand. The crop sensor-based approach is more promising, because it is non-destructive and allows real-time diagnosis and recommendation in the field, and deserves more research in China.

5. CONCLUSION AND FUTURE DIRECTIONS

Chinese farmers accumulated rich experiences in integrated and efficient utilization of different strategies of crop rotation, intercropping, and all possible resources of organic manures to produce modest crop yield and maintain soil fertility using traditional farming practices. However, to feed the increasing population with decreasing land and other resources, this precious experience is gradually being abandoned and nutrient management shifted to over-reliance on chemical fertilizers. Over-application of N has become common in intensive agricultural regions, leading to low nutrient-use efficiency and environmental pollution, which threatens long-term sustainability of Chinese agriculture. Many factors may have contributed to the over-application problems in China, including high yield as a top priority, small-scale farming, lack of temporal synchronization of nitrogen management, lack of effective extension systems, and hand application of fertilizers by farmers.

A review of long-term experiments conducted around the world indicates that chemical fertilizer alone is not enough to improve or main soil fertility at high levels and over-application of synthetic N fertilizers can result in significant soil acidification problems, which can be reduced if more fertilizer N is applied as NO_3^- relative to ammonium- or urea-based N fertilizers. Organic fertilizers can improve soil fertility and quality, but long-term application at high rates can also lead to more nitrate leaching, and accumulation of P, if not managed well. The combination of chemical and organic fertilizers can not only achieve higher yields, but also improve soil fertility and quality and alleviate soil acidification problems compared with only using chemical fertilizers, and thus is more sustainable. Increasing temporal diversity through crop rotation is an important strategy to crease crop yield and sustainability, and legume-based cropping systems can reduce carbon and nitrogen losses and should be incorporated into nutrient management systems. Crop yield responses to N fertilization can vary significantly from year to year due to variation in weather conditions and indigenous N supply, thus the commonly adopted prescriptive approach to N management needs to be replaced by a responsive in-season management approach based on diagnosis of crop growth and N status and demand. A crop sensor-based in-season N management strategy has been demonstrated in the North China Plain to achieve N-uptake efficiency of 61.3%, which is 368% higher than the farmers' practices.

To develop sustainable nutrient management systems in China that can not only improve nutrient-use efficiency but also significantly increase crop yield is very challenging. This will require a combination of well-tested principles and practices in traditional agriculture and modern crop management technologies. For example, the integrated and efficient utilization of different strategies of crop rotation, intercropping, all possible resources of organic manures, green manures and crop residues as well as nutrients from soil, atmospheric deposition and irrigation water, etc. to maintain crop yield and soil fertility needs to be emphasized, legumes should be integrated into the cropping systems as much as possible, new sensing technologies should be developed and used to estimate nutrient content better and supply of different organic fertilizers, diagnose crop nutrient status and determine crop nutrient demand during the growing season, and chemical fertilizers should be applied as supplements only when and where nutrients from other resources are not enough to meet crop requirements. Such precision nutrient management systems should not only match field-to-field and year-to-year variability in nutrient supply and crop demand for single crops, but for crop rotations as integrated systems as well (Spiertz, 2010), leading to more balanced nutrient management, less reliance on chemical fertilizers, and improved nutrient-use efficiencies as well as higher crop yield. Such complicated technologies need to be simplified to be farmer-friendly and suitable for small-scale farming. They need to be reliable, easy to use and cheap. Ultimately, it is the individual farmer who will make the decision about what to apply, how much to apply, when to apply and how to apply. This imposes great limitations on what can be done toward sustainable nutrient management in China. To meet the challenge, however, this limitation has to be overcome. A great need is to develop innovative and effective extension and service-providing systems to assist the farmers in adopting new technologies. Such systems should be capable of farmer-specific recommendations, and have easy access to advanced technologies. Such systems should maintain close relationships with producers, researchers and the government, and be supported by both the government and users. Without such effective systems, it would not be realistic to rely on the scientists or the 240 million households alone to meet the grand challenge of food security, nutrient-use efficiency and environmental protection in China.

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