AMBIO (2010) 39:376–384
DOI 10.1007/s13280-010-0076-6

REPORT

Current Nitrogen Management Status and Measures to Improve the Intensive Wheat–Maize System in China

Zhenling Cui, Xinping Chen, Fusuo Zhang

Received: 7 July 2009 / Revised: 27 April 2010 / Accepted: 5 May 2010 / Published online: 22 July 2010

Abstract During the first 35 years of the Green Revolution, Chinese grain production doubled, greatly reducing food shortage, but at a high environmental cost. In 2005, China alone accounted for around 38% of the global N fertilizer consumption, but the average on-farm N recovery efficiency for the intensive wheat–maize system was only 16–18%. Current on-farm N use efficiency (NUE) is much lower than in research trials or on-farm in other parts of the world, which is attributed to the overuse of chemical N fertilizer, ignorance of the contribution of N from the environment and the soil, poor synchrony between crop N demand and N supply, failure to bring crop yield potential into full play, and an inability to effectively inhibit N losses. Based on such analyses, some measures to drastically improve NUE in China are suggested, such as managing various N sources to limit the total applied N, spatially and temporally matching rhizospheric N supply with N demand in high-yielding crops, reducing N losses, and simultaneously achieving high-yield and high NUE. Maximizing crop yields using a minimum of N inputs requires an integrated, interdisciplinary cooperation and major scientific and practical breakthroughs involving plant nutrition, soil science, agronomy, and breeding.

Keywords Nitrogen management · Nitrogen use efficiency · Environment · Crop yield · China

INTRODUCTION

Chinese agricultural production has obtained worldwide recognition in the last 50 years by creating the world's "Miracle in China." China has 9% of the world's arable land and feeds 22% of the world population. Crop grain production has grown dramatically, increasing about five-fold from 113 million tons in 1949 to 512 million tons in 1998, which is an annual increase rate of 9% (China Agricultural Yearbook 1999). In 1998, Chinese grain, meat, and egg production per capita exceeded the world average (FAOSTAT 2002; Zhu and Chen 2002). The ability of the Chinese to produce grain for their own consumption is a key factor for sustaining the future global food supply at affordable world market prices. China is also a key determinant of anthropogenic changes in the global N cycle, due to its role as the word's largest consumer of N fertilizers (Galloway and Cowling 2002; Smil 2001). China's N fertilizer consumption became the highest in the world in 1985 and increased to 38% of the world's total N production in 2005 (FAOSTAT 2006). Furthermore, the combination of soaring incomes and population growth in China in the next 30 years is expanding the demand for food and the application of N fertilizer on a scale never seen before. Therefore, improving N management practices and policy in China is a worldwide concern.

Improving N management is required to understand the contribution of a farmer's behavior to current N application practical problems, such as N use efficiency (NUE) of the main cereal production system (Cassman et al. 2002; Dobermann 2005). However, a paucity of reliable data on N management exists based on measurements from on-farm studied major cereal production systems in China. This shortage of information has resulted in difficulties in developing management strategies to improve farmers' N practices on a large scale and project the amounts of N fertilizer needed to meet the increasing food demand (Ladha et al. 2005).

Here, we evaluated the current N management status and NUE of the intensive wheat–maize system in China to explain the main reason for the low NUE and suggest measures for improvement. The focus of the article is on the NUE of the intensive wheat–maize system because it provides more than 50% of the food production in China (China Agricultural Yearbook 1999). We define the NUE of a cropping system as the proportion of N fertilizer that is removed from the harvested crop biomass during the growing season (REN, N recovery efficiency) and the ratio of crop yield per unit of applied N fertilizer (PFPN, partial factor productivity) (Dobermann 2005; Ladha et al. 2005; Novoa and Loomis 1981).

CURRENT STATUS OF NITROGEN USE EFFICIENCY IN CHINA

Available data indicate a very low 16–18% average for on-farm REN and a PFPN of 30–37 kg kg^{-1} for the intensive wheat–maize system. In practice, the REN is close to zero at some sites (Table 1). The ^{15}N results in an intensive wheat–maize system showed that only 25% of the N fertilizer applied is absorbed by crops, 25–45% is accumulated in soil, and 30–50% is lost to the environment (Pan 2001). Similar results showed that the average REN for farmers' fields was only 10% (Ma 1999) and 11–20% in the intensive wheat–maize system (Zhao 2006). In contrast, the on-farm maize REN in the U.S. Corn Belt was 37%, which is more than twice that of China (Cassman et al. 2002). Within research trials, the estimated average "global" REN is 54 and 63% for wheat and maize, respectively (Table 1).

In China, the estimated REN from experimental sites (26–28%) is more than 10% greater than within a farmer's N practice (16–18%) (Zhang et al. 2008). The same result was also observed for the PFPN. This result is consistent with early observations that estimates of NUE from experimental plots do not accurately represent the efficiencies achieved in farmers' fields (Cassman et al. 2002). A lower NUE in a farmer's field is usually explained by lower management quality under practical farming conditions, excessive N application rate, and a greater spatial variability of factors controlling the NUE. This is further supported by the finding that on-farm NUE varies widely among farmers, with good farmers already achieving an REN > 50%. Clearly, REN in well-managed experiments is generally greater than the efficiency of the same practice applied by farmers in a production field. Considering this, the NUE from research trials is a good indicator of what can be achieved with good management, but a farmer's behavior must be assessed to develop the optimal N management strategy using these results.

The current REN in China has significantly declined from 35% in 1980 to 26–28% in research trials to 16–18% in farmers' fields (Zhu and Wen 1992). This result is consistent with the observation that the PFPN in the intensive wheat–maize system has decreased from 46 kg kg^{-1} with a 174 kg N ha^{-1} year^{-1} application rate in 1978 to 21 kg kg^{-1} with a 592 kg N ha^{-1} year^{-1} application rate in 1998 (Fang et al. 2006). In contrast, in many developed countries, the average PFPN has remained virtually unchanged at 49 kg kg^{-1}, and has even steadily increased in some areas since the mid 1980s, i.e., in Western Europe, North America, Japan, and South Korea (Dobermann and Cassman 2005). The global PFPN for cereals should increase at a rate of 0.1 to 0.4 kg kg^{-1} year^{-1} to meet the 2025 cereal demand (Dobermann and Cassman 2005).

REASONS FOR DECLINING N USE EFFICIENCY

Overuse of Chemical N Fertilizers

Based on numerous on-farm investigations from 1997 to 2007 (Zhao 1997; Chen 2003; Cui 2005; Ma et al. 1999),

Table 1 Nitrogen recovery efficiency (REN) and partial factor productivity (PFPN) for wheat and maize in different locations and different years

Locations and years	Crop type	No. of trails	N rate (kg N ha^{-1})	REN (%)	PFPN (kg kg^{-1})	References
North China, 2002–2006	Wheat, on-farm	121	326	18% (5–50%)	20 (8–43)	Cui et al. (2008b)
China, 2001–2005	Wheat, research trials	273	169	28% (11–41%)	43	Zhang et al. (2008)
World	Wheat, research trials	507	117	54	–	Ladha et al. (2005)
North China, 2002–2006	Maize, on-farm	148	263	16% (−2 to 48%)	37 (18–78)	Cui et al. (2008a)
China, 2001–2005	Maize, research trials	215	162	26% (16–26%)	52	Zhang et al. (2008)
World	Maize, research trials	36	102	63	–	Ladha et al. (2005)
USA	Maize, on-farm	55	103	37	–	Cassman et al. (2002); Dobermann (2005)
China, 1980s	Grain crops, research trials	478		35% (28–41%)		Zhu and Wen (1992)

the typical N rate for farmers was more than 500 kg N ha^{-1} year^{-1} for the intensive wheat–maize system in China and approached 600 kg N ha^{-1} year^{-1} in some regions (Table 2). Correspondingly, average grain yields were around 11.5 ha^{-1} year^{-1} (around 5.5 and 6.0 t ha^{-1} for wheat and maize, respectively), and the estimated N uptake was only 200 kg N ha^{-1} year^{-1} (around 160 and 140 kg N ha^{-1} for wheat and maize, respectively). Results from region-wide experiments have demonstrated that the economically optimal N rate is from 130 to 160 kg N ha^{-1} crop^{-1} for the intensive wheat–maize system (Cui et al. 2008a, b). Clearly, N fertilizer applications have far exceeded crop requirements for maximum wheat and maize yield in China, and much of the excess N fertilizer is lost to the environment, degrading both air and water quality.

Affected by simultaneous increases in N fertilizer application rates and grain yields before the mid 1990s, most extension staff and farmers still believed that more fertilizer and higher grain yields are synonymous. We observed in our investigation that about 67% of farmers add excessive N fertilizer in pursuit of higher grain yields, and 45% of farmers thought soil productivity would be affected 1 year after reducing their current N application rate (Cui ZL, unpublished data). Small-scale farming with high variability between fields and poor infrastructure in the extension service has resulted in a duplication of effort and low efficiency for current N management practices in China. Farmers get about 30% of their fertilization information from the fertilizer dealer, 30% from their neighbors, and 30% from experience, and they receive less than 10% of their fertilizer information from extension services. As a result, most Chinese farmers have no idea of the appropriate amount of N fertilizer, and apply a large amount of N fertilizer at a uniform rate as an “insurance” against low yields (Ma 1999; Zhao 2006; Ma et al. 1999). In addition, the high off-farm incomes and relatively low retail prices of N fertilizers (with government subsidies for production and transportation) also encourage farmers to continuously increase the application of N.

Ignorance of N Contributed by the Soil and Environment

With the increase in the amount of N fertilizer applied and aggravation of environmental pollution, N supplied from the soil and environment is becoming an important N source in China. Across numerous on-farm experiments ($n = 269$), indigenous N supply (average N uptake at 0 N control) typically provides around 274 kg N ha^{-1} year^{-1} and accounts for 76% of crop N uptake within the intensive wheat–maize system (Cui et al. 2008a, b). As a result, finding high yields with no application of N fertilizer is not uncommon (Tong et al. 2004). This large indigenous N supply aggravates N surpluses and increases the potential for N losses from agroecosystems unless it is considered as part of the plant-available N supply when constructing a N management plan.

The large indigenous N supply is attributable to high soil nitrate–N accumulation, net soil N mineralization, and environmental N supply. Pooling data from all on-farm investigations in the wheat–maize system in China, the soil nitrate–N accumulation in the 0–90 cm soil profile before planting is around 190 kg N ha^{-1}, which is close to the amount of N fertilizer needed for maximum grain yield value in response to added N fertilizer (Ju et al. 2004, 2006; Liu et al. 2004; Cui et al. 2008a, b). The amount of net N mineralized is around 172 kg N ha^{-1} year^{-1}. Total environmental N inputs reach approximately 104 kg N ha^{-1} year^{-1}, including approximately 89 kg of N deposited ha^{-1} year^{-1} from the atmosphere, and 15 kg of irrigation-N ha^{-1} (Liu et al. 2006; Ju et al. 2009). Although the indigenous N supply has a very high N-fertilizer substitution value (Cassman et al. 2002), many current N practice and management strategies in China do not take this into account when making N management plans.

Table 2 Nitrogen fertilizer application rate by typical survey conducted for wheat and maize in different locations and different years (kg N ha^{-1} crop^{-1})

Locations and years	No. of investigated fields	Chemical N rate		Organic N rate		References
		Wheat	Maize	Wheat	Maize	
Beijing, 1997	250	309	256	–	–	Zhao (1997)
Henan, 2008	452	213	270	22	24	Ye YY unpubl. data
XJ, Hebei, 2000	20	273	191	–	–	Chen (2003)
HM, Shandong, 2003	368	365	249	59	–	Cui (2005)
Shandong, 2004	>500	256	243	–	–	Ye YY unpubl. data
Shandong, 1997	1,046	288	209	90	12	Ma et al. (1999)
Shandong, 2005	1,690	305	248	52	10	Cui ZL unpubl. data

Poor Synchrony Between Crop N Demand and N Supply from all Sources

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 N supply rate is usually about 50% of the total amount given (Chen 2003; Cui et al. 2008a, b). Clearly, this large amount of N fertilizer input in the early growth stages has resulted in poor synchrony between soil N supply and crop demand, which leads to high soil inorganic N levels well before rapid crop N uptake occurs (Ayoub et al. 1995; Chen et al. 2006; Tilman et al. 2002).

Nitrogen application in excess of crop N demand at the early growth stage increases the potential for nitrate–N leaching and results in excessive crop growth that is more susceptible to disease infection and wheat lodging. Applying N fertilizer near to the time it is needed by the crop increases crop grain yield and improves NUE (Russelle et al. 1981; Welch et al. 1971). Results from Iowa (Sanchez and Blackmer 1988) indicate that 50–64% of fall-applied N is lost from the upper 1.5 m of soil by processes other than crop uptake. Results from Spain (Lopez-Bellido et al. 2005) also show that mean wheat use of N fertilizer ranges from 14.1% when applied at sowing to 54.8% when applied as topdressing at the beginning of stem elongation.

Failure to Bring Crop Yield Potential into Full Play

Chinese crop grain production has been stagnant since 1998, and only 431 million tons were produced in 2003 (84% of that in 1998) (FAOSTAT 2006). Stagnating crop grain yields and rapidly increasing N application has contributed to a decline in the low NUE. In contrast, in many industrialized countries of the Western world, cereal yields have continued to increase, but N use has either remained constant or declined since 1980 (Dobermann 2005; Dobermann and Cassman 2005).

In recent years, China has had record high crop yields, and the maximum gain in yield for wheat and maize has more than 11 and 16 t ha^{-1} in some research trials, respectively (Shan 2001; Chen et al. 2008). However, Chinese wheat and maize production averaged only 4.5 and 5.3 t ha^{-1} in 2006, respectively, and even in some high-yield regions, grain yields do not exceed 6.5 t ha^{-1} $crop^{-1}$. While achieving record high yield in farmers' fields is impossible, low grain yield suggests a major opportunity to increase the current grain yield. High grain yield can contribute to greater NUE from both indigenous and applied N sources because fast-growing plants have root systems that more effectively exploit available soil resources (Burns 1980).

Inability to Effectively Inhibit N Losses

Ammonia volatilization, nitrate leaching, and denitrification are the major contributors to N losses. With calcareous soils, a pH around 8, and the predominant use of urea and ammonium bicarbonate as mineral N fertilizer, NH_3 volatilization is generally viewed as a major pathway for N losses in the intensive wheat–maize system in China (Zhu and Wen 1992; Ju et al. 2009). Here, we summarize recent NH_3 volatilization results using a wind tunnel system, a micrometeorological (gradient diffusion) and Bowen ratio system, and observed that NH_3 volatilization accounts for an average 22% of applied N fertilizer (Table 3) (Zhang et al. 1992, 2005; Li et al. 2002a, b; Su et al. 2007). Peak NH_3 volatilization occurs 2–3 weeks after N fertilization and irrigation. Wet soil conditions and higher summer temperatures raise the potential for NH_3 volatilization and N_2O emissions during the maize-growing season (Ju et al. 2009; Zhang et al. 2005). Compared to the high losses from NH_3 volatilization, denitrification losses are quite small in the intensive wheat–maize system and account for less than 5% of the applied N fertilizer (Zhang et al. 2005).

In the past, little attention was paid to nitrate–N leaching in wheat–maize system, where the climatic water balance is negative. In this region, the average annual precipitation is about 500–600 mm, whereas evapotranspiration of the winter wheat–summer maize rotation system requires more than 800 mm (Wang et al. 2001). Early lysimeter experiments indicated that leaching losses in the wheat–maize system account for less than 10% of the applied N fertilizer, most of which occurs only during the summer season (Ju et al. 2009; Yuan et al. 1995) (Fig. 1).

However, increasing evidence indicates that leaching losses occur in this region. Wheat and maize grow in a warm, subhumid continental monsoon climate, with cold winters and hot summers; 70–80% of the rainfall occurs during the maize-growing season in summer and more than 100 mm often falls at one time. In order to achieve a high wheat yield, irrigation water is applied up to three times (>90 mm per time) during the wheat-growing season (Li et al. 2005; Sun et al. 2006). As a result, high leaching losses often occur due to a rainfall concentration during the maize-growing season or through overuse of irrigation water during the wheat-growing season (Chen 2003; Ju et al. 2006, 2009).

Due to excessive long-term fertilization, higher soil nitrate–N has accumulated in the intensive wheat–maize system. Ju et al. (2006) observed that residual soil nitrate–N after winter wheat harvest was 275 kg N ha^{-1} in the top 90 cm of the soil profile and 213 kg N ha^{-1} at the 90–180 cm soil depth increment. Our results clearly demonstrate that like a time bomb that could explode at any

Table 3 Ammonia volatilization as a percentage of N application rate with different fertilization methods, crops, N rate and N source

Fertilization methods	Crop[a]	N rate ($kg\ N\ ha^{-1}$)	NH_3 volatilization (%)	N source	References
Surface-broadcast	M	–	30	Urea	Zhang et al. (1992)
	M	186	25	Urea	Li et al. (2002a)
	M	148	37	Ammonium bicarbonate	Li et al. (2002a)
	M	157	27	Urea	Zhang et al. (2005)
	W	110	15	Urea	Zhang et al. (2005)
	W	150	24	Urea	Zhang et al. (2005)
Broadcast before irrigation or plowing, or point deep-placed	W	191–210	10–12	Ammonium bicarbonate	Li et al. (2002b)
	W	300	19	Urea	Li et al. (2002b)
	M	300	25	Urea	Li et al. (2002b)
	M	50–117	27	Urea	Su et al. (2007)
	W–M	–	24–37	Urea	Su et al. (2007)

[a] W, M and W–M is wheat, maize, and wheat-maize systems, respectively

Fig. 1 Over-use nitrogen and water for winter wheat production in the North China Plain (Shandong, Huimin, 2003)

moment, high soil nitrate–N accumulation moves to a deeper soil layer to be leached at any time given the right climatic conditions (Zhao et al. 2006). The same results have been observed in China (Ju et al. 2009) and in Britain (Davies and Sylvester-Bradley 1995).

MEASURES FOR IMPROVING N MANAGEMENT

Managing Various N Sources to Limit the Total Applied N

Since the 1990s in China, excessive mineral N fertilization has often been considered main practice strategy to pursue high yield. The average N fertilizer application rate has far exceeded crop requirements for maximum grain yield, even with the double-crop N demand in some areas (Table 2). Clearly, applying large amounts of N fertilizer not only affects grain yield and N uptake, but also increases the potential for N losses to the environment. For example, N fertilizer could be cut from 588 to 286 $kg\ N\ ha^{-1}\ year^{-1}$ without a loss in yield or grain quality, and in the process, reduce N losses by <50% (Ju et al. 2009). Therefore, we believe that “limiting the total fertilizer N application rate” should be a top policy priority and practice in China.

Considering various N sources from the soil and environment and a large number of on-farmer field experiments, the regional mean optimal N rate (RMONR) is recommended to be 150–180 $kg\ N\ ha^{-1}\ crop^{-1}$ for the intensive wheat–maize system in China (Zhu 1998; Zhang et al. 2002). In practice, it should be adjusted according to the local conditions, such as yield, variety, irrigation, and soil fertility. This N recommendation based on the RMONR is slightly higher than the economically optimal N application rate (130–160 $kg\ N\ ha^{-1}\ crop^{-1}$) by soil and plant N monitoring but is significantly lower than the 250–300 $kg\ N\ ha^{-1}\ crop^{-1}$ currently used by farmers. Although RMONR is semiquantitative, it provides a rough range to avoid N-deficient reduced yields and profit, and N overuse increased N losses, and can be used as a reference for extension technicians without any soil and/or plant N monitoring. In addition, this recommendation can be easily adopted in rural areas of China where no available soil and/or plant N monitoring facilities exist and the cropping index is high, such as in the intensive wheat–maize system (Zhu and Chen 2002).

Spatially and Temporally Matching the Rhizospheric Nitrogen Supply with the Nitrogen Demand of High-Yielding Crops

Recent literature on improving the REN in crop production has emphasized the need for greater synchrony between crop N demand and N supply from all sources throughout the growing season (Cassman et al. 2002; Dobermann 2005; Tilman et al. 2002). Considering site-specific soil N supply and crop demand, early research has demonstrated that in-season applied N results in a high NUE (Flowers et al. 2004; Shanahana et al. 2007). As a net result of soil N transformation, transport, fertilizer applications, and environmental N supply, soil N supply significantly contributes to the crop N requirement. Therefore, N management leads to an improvement in soil N supply to the root zone within a reasonable range that matches the required quantity and is synchronized in terms of time and crop growth and coupled in space to the N supply and crop N requirements.

Dry matter production and thus N requirement is rather low before the crops are growing rapidly, i.e., stem elongation of wheat and the six-leaf stage of maize. In most cases, a small amount of N fertilizer and indigenous N supply can meet the crop N requirement, establish growth, and promote the development of healthy roots during the early periods of crop growth (Cui et al. 2008c, d). Nitrogen application in excess of crop N demand during this period increases the potential for nitrate–N leaching and results in excessive crop growth that is more susceptible to disease and lodging. Therefore, more N fertilizer (around 60–70% of the total N fertilizer applied) should be applied during the fastest growing stages of the crop to achieve synchrony between the N supply and crop demand. This is consistent with early observations that N fertilizer should be applied close to the peak N uptake to increase grain yield and NUE and decrease the opportunity for soil N losses (Russelle et al. 1981; Welch et al. 1971).

Although the average N application rate in China is excessive for the maximum N crop requirement, some low-income farmers or those in remote areas have deficient N application rates. If we simply use 150–200 kg N ha^{-1} as a reasonable amount of N fertilizer for the main wheat and maize-growing regions of China ($n = 10{,}000$), only one-third of farmers would be in this range, one-third would be applying too much, and one-third would be applying too little (Wang 2007). On a regional scale, higher crop yields are likely to be achieved through a combination of increased N application in regions with low N fertilizer use, and improved NUE in regions where N fertilizer use is already high.

Reducing N Losses

In practice, the amount of NH_3 volatilization is largely influenced by fertilization methods and N fertilizer type. Deep placement of urea or ammonium bicarbonate improves the NUE. For example, N loss through NH_3 volatilization during the maize-growing season can be reduced from 30–48% to 11–18% of applied urea-N fertilizer when applied deep as compared to a surface broadcast (Zhang et al. 1992; Li et al. 2002a). In China, N is generally recommended to be applied to wheat before irrigation because of a very low recovery of broadcast urea when precipitation is low and the fertilizer cannot reach the rooting zone. In contrast, when urea is applied before irrigation or plowing, NH_3 volatilization is significantly reduced, indicating the necessity for irrigation or rainfall to leach N fertilizer into the rooting zone (Table 3).

The strategy of reducing nitrate leaching sounds simple: decrease nitrate–N content in the soil profile. For environmentally friendly crop production, residual soil nitrate–N content should be minimized, especially at the end of the growing season, because nitrate–N leaching is directly related to the mineral N content in the root zone (Roth and Fox 1990; Sogbedji et al. 2000; Dinnes et al. 2002). However, achieving high maize yields is impossible if nitrate–N in the root zone is too low. It then becomes important to consider "the suitable soil nitrate–N level in which the lower limit does not restrict grain yield, and the upper limit does not lead to unacceptable N losses to the environment." Within the European experience as well as our results (Cui et al. 2008c, d; Schleef and Kleihanss 1994; Hofman 1999), residual nitrate–N content after harvest in the top 90 cm soil layer should be maintained around 90 kg N ha^{-1}. When soil profile inorganic N exceeds 190 kg nitrate–N ha^{-1} in the top 90 cm of soil before planting, an increase in grain yield in response to added N is unlikely within the intensive wheat–maize system in China (Cui et al. 2008c, d).

Simultaneously Achieving High Yield and High N Use Efficiency

While considerable progress has been made toward increasing crop yields and improving resource efficiency in China, simultaneously enhancing the yield and resource efficiency has met with limited success. Increasing crop productivity and improving NUE is not only related to maximizing the biological potential of crops, but is also key for the sustainability of agricultural production.

Maximizing crop yields using a minimum N input requires an integrated, interdisciplinary cooperation and major scientific and practical breakthroughs involving plant nutrition, soil science, agronomy, and breeding. Given the difficulties of raising yields by increasing harvest index to crops, establishing ideal crop canopy groups with a large total storage capacity (total number per group) and high material accumulation post-anthesis will be crucial to enhance the biological yield per unit area and promote the greatest agronomic performance between individuals and groups (Shearman et al. 2005; Peng and Khush 2003). In practice, ideal crop canopy groups can be achieved by maintaining the appropriate leaf area index to enhance the rate of panicle and seed setting rate, and the late extension of leaf area to improve the photosynthetic rate and the efficiency of material assimilate distribution.

Current N management strategies aim to deliver soluble inorganic N directly to the crops, but are unrelated to carbon, N, and phosphorus cycles in space and time. As a result, agricultural ecosystems are maintained in a state of N saturation and are inherently leaky because chronic surplus additions of N are required to meet yield goals (Drinkwater and Snapp 2007). Crop yield can be increased while minimizing fertilizer application by managing the N supply in the root zone within a reasonable range, which realizes the biological potential of crops, matches high-yield crop N requirement, and controls for minimal N losses. Nitrogen supply and N requirements in the high-yielding crop systems must be matched in quantity and synchronized in terms of time, as well as consider spatial linkages. Some changes must be made to achieve this goal: using a variety of N sources for fertilizer, calculating the balance between the input and output to manage a variety of intrinsic ecosystem processes at multiple scales to re-couple elemental cycles, and considering the biological potential of the root system and matching crop requirements by only supplying sufficient N when full plant demand exists.

PERSPECTIVES

Nitrogen use efficiency can be improved in China by adopting integrated fertilizer, soil, water, and crop management practices to maximize crop N uptake and minimize N losses. Management strategies that increase N fertilizer use by crops should focus on two approaches: increasing N fertilizer use during the growing season when the fertilizer is applied and decreasing fertilizer N losses by optimally applying N fertilizer through good crop management. Increasing yield by removing plant growth limiting factors would increase crop N demand and lead to a greater use of available resources and a higher NUE.

However, sustained benefits from the addition of N and meaningful abatement of N losses will require policies that promote the adoption of research proven practices that reward environmental performance as well as high yields. The Chinese government has been aware of this and is increasing investment for research and agricultural subsidies to reward sustainable practice. For example, the Chinese National Soil Testing and Fertilizer Recommendation Program were started in 2005 and has already become part of a national agricultural technique policy. In 2009, 2,500 counties were involved and received 1.5 billion yuan in financial support from the central government to demonstrate soil testing and fertilizer recommendations. The expectation of these supports for research and demonstration has been to increase our ability to understand how to simultaneously achieve both high yield and a high NUE and adopt research-proven practices that maximize grain yield as well as minimize N losses to the environment.

REFERENCES

Ayoub, M., A. Mackenzie, and D.L. Smith. 1995. Evaluation of N fertilizer rate, timing and wheat cultivars on soil residual nitrates. *Journal of Agronomy and Crop Science* 175: 87–97.

Burns, I.G. 1980. Influence of the spatial distribution of nitrate on the uptake of N by plants: A review and a model for rooting depth. *Journal of Soil Science* 31: 155–173.

Cassman, K.G., A. Dobermann, and D.T. Walters. 2002. Agroecosystems, nitrogen use efficiency, and nitrogen management. *Ambio* 31: 132–140.

Chen, X.P. 2003. *Optimization of the N fertilizer management of a winter wheat/summer maize rotation system in the North China Plain*. PhD Thesis, University of Hohenheim, Stuttgart, Germany.

Chen, G.P., G.H. Yang, M. Zhao, and J.R. Zhao. 2008. Studies on maize small area super-high yield trails and cultivation technique. *Journal of Maize Science* 16: 1–4. (in Chinese).

Chen, X.P., F.S. Zhang, and V. Römheld. 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.

China Agricultural Yearbook. 1999. *Editorial Committee of China Agricultural Yearbook*, 587–605. Beijing: China Agricultural Publishing House. (in Chinese).

Cui, Z.L. 2005. *Optimization of the nitrogen fertilizer management for a winter wheat–summer maize rotation system in the North China Plain—From field to regional scale*. PhD Thesis, China Agricultural University, Beijing, China (in Chinese with English summary).

Cui, Z.L., X.P. Chen, F.S. Zhang, Y.X. Miao, and J.L. Li. 2008a. On-farm evaluation of the improved soil N_{min}-based nitrogen management for summer wheat in North China Plain. *Agronomy Journal* 100: 517–525.

Cui, Z.L., Y.X. Miao, F.S. Zhang, and X.P. Chen. 2008b. Soil nitrate-N levels required for high yield maize production in the North China Plain. *Nutrient Cycling in Agroecosystems* 82: 187–196.

Cui, Z.L., F.S. Zhang, X.P. Chen, Miao, and J.L. Li. 2008c. On-farm evaluation of an in-season nitrogen management strategy based on soil N_{min} test. *Field Crops Research* 105: 48–55.

Cui, Z.L., F.S. Zhang, Y.X. Miao, and X.P. Chen. 2008d. On-farm evaluation of winter wheat yield response to residual soil nitrate-N in North China Plain. *Agronomy Journal* 100: 1527–1534.

Davies, D.B., and R. Sylvester-Bradley. 1995. The contribution of fertilizer nitrogen to leachable nitrogen in the UK: A review. *Journal of the Science of Food and Agriculture* 68: 399–406.

Dinnes, D.L., D.L. Karlen, D.B. Jaynes, T.C. Kaspar, J.L. Hatfield, T.S. Colvin, and C.A. Cambardella. 2002. Nitrogen management strategies to reduce nitrate leaching in tile-drained midwestern soils. *Agronomy Journal* 94: 153–171.

Dobermann, A. 2005. *Nitrogen use efficiency state of the art*. Paper of the IFA international workshop on enhanced efficiency fertilizers. Frankfurt, Germany.

Dobermann, A., and K.G. Cassman. 2005. Cereal area and nitrogen use efficiency are drivers of future nitrogen fertilizer consumption. *Science in China Series C: Life Sciences* 48: 745–758.

Drinkwater, L.E., and S.S. Snapp. 2007. Nutrients in agroecosystems: Rethinking the management paradigm. *Advances in Agronomy* 92: 163–186.

Fang, Q.X., Q. Yu, E.L. Wang, Y.H. Chen, G.L. Zhang, and J. Wang. 2006. Soil nitrate accumulation, leaching and crop nitrogen use as influenced by fertilization and irrigation in an intensive wheat–maize double cropping system in the North China Plain. *Plant and Soil* 284: 335–350.

FAOSTAT. 2002. *FAO Statistical Databases*. Agriculture Data. http://apps.fao.org/page/collections?subset=agriculture.

FAOSTAT. 2006. *FAO Statistical Databases*. Agriculture Data. http://apps.fao.org/page/collections?subset=agriculture.

Flowers, M., W. Randall, H. Ronnie, O. Deanna, and C. Carl. 2004. In-season optimization and site-specific nitrogen management for soft red winter wheat. *Agronomy Journal* 96: 124–134.

Galloway, J.N., and E.B. Cowling. 2002. Reactive nitrogen and the world: 200 years of change. *Ambio* 31: 64–71.

Hofman, G. 1999. *Nutrient management legislation in European countries*. NUMALEC Report. Concerted action, Fair6-CT98-4215.

Ju, X.T., C.L. Kou, F.S. Zhang, and P. Christie. 2006. Nitrogen balance and groundwater nitrate contamination: Comparison among three intensive cropping systems on the North China Plain. *Environmental Pollution* 143: 117–125.

Ju, X.T., X.J. Liu, F.S. Zhang, and M. Roelcke. 2004. Nitrogen fertilization, soil nitrate accumulation, and policy recommendations in several agricultural regions of China. *Ambio* 33: 300–305.

Ju, X.T., G.X. Xing, X.P. Chen, and X.B. Zhang. 2009. Reducing environmental risk by improving N management in intensive Chinese agricultural systems. *Proceedings of the National Academy of Sciences* 106: 3041–3046.

Ladha, J.K., H. Pathak, T.J. Krupnik, J. Six, and C. Kessel. 2005. Efficiency of fertilizer nitrogen in cereal production: Retrospects and prospects. *Advances in Agronomy* 87: 86–156.

Li, G.T., B.G. Li, and D.L. Chen. 2002a. Method for measurement of ammonia volatilization from large area field by Bowen Ratio System. *Journal of China Agricultural University* 6: 56–62. (in Chinese with English abstract.).

Li, G.T., B.G. Li, and D.L. Chen. 2002b. Ammonia volatilization from large field planted with winter wheat and summer maize. *Acta Agriculture Boreall-sinica* 17: 76–81. (in Chinese with English abstract.).

Li, J.M., S. Inanaga, Z.H. Li, and A.E. Eneji. 2005. Optimizing irrigation scheduling for winter wheat in the North China Plain. *Agricultural Water Management* 75: 8–23.

Liu, X.J., X.T. Ju, and Y. Zhang. 2006. Nitrogen deposition in agroecosystems in the Beijing area. *Agriculture, Ecosystems & Environment* 113: 370–377.

Liu, H.B., Z.H. Li, and Y.G. Zhang. 2004. Characteristics of nitrate distribution and accumulation in soil profiles under main agro-land use types in Beijing. *Scientia Agricultura Sinica* 37: 692–698. (in Chinese with English abstract.).

Lopez-Bellido, L., R.J. Lopez-Bellido, and R. Redondo. 2005. Nitrogen efficiency in wheat under rainfed Mediterranean conditions as affected by split nitrogen application. *Field Crops Research* 94: 86–97.

Ma, W.Q. 1999. *Current status and evaluation of crop fertilization in Shandong province*. PhD Thesis, China Agricultural University, Beijing, China (in Chinese with English summary).

Ma, W.Q., D.R. Mao, and F.S. Zhang. 1999. Current status and evaluation of crop fertilization in Shandong province. *Chinese Journal of Soil Science* 30: 217–220. (in Chinese with English summary).

Novoa, R., and R.S. Loomis. 1981. Nitrogen and plant production. *Plant and Soil* 58: 177–204.

Pan, J.R. 2001. *Fate of fertilizer nitrogen in winter wheat-summer maize rotation system at North China Plain*. PhD Thesis, China Agricultural University, Beijing, China (in Chinese with English summary).

Peng, S., and G.S. Khush. 2003. Four decades of breeding for varietals improvement of irrigated lowland rice in the international rice research institute. *Plant Production Science* 6: 157–164.

Roth, G.W., and R.H. Fox. 1990. Soil nitrate accumulation following nitrogen fertilized corn in Pennsylvania. *Journal of Environment Quality* 9: 243–248.

Russelle, M.P., E.J. Deibert, R.D. Hauck, M. Stevanovic, and R.A. Olson. 1981. Effects of water and nitrogen management on yield and 15N-depleted fertilizer use efficiency of irrigated corn. *Soil Science Society of America Journal* 45: 553–558.

Sanchez, C.A., and A.M. Blackmer. 1988. Recovery of anhydrous ammonia derived nitrogen-15 during three years of corn production in Iowa. *Agronomy Journal* 80: 102–108.

Schleef, K.H., and W. Kleihanss. 1994. *Mineral balance in agriculture in EU*. Brounchweig, Germany: Institute of farm economics, Federal Agricultural Research Centre.

Shan, Y.S. 2001. *Theory of high-yield wheat cultivation techniques*. Beijing: Science Press. (in Chinese).

Shanahana, J.F., N.R. Kitchenb, and W.R. Raunc. 2007. Responsive in-season nitrogen management for cereals. *Computers and Electronics in Agriculture Archive* 61: 51–62.

Shearman, V.J., R. Sylvester-Bradley, R.K. Scott, and M.J. Foulkes. 2005. Physiological processes associated with wheat yield progress in the UK. *Crop Science* 45: 175–185.

Smil, V. 2001. *Enriching the earth*, 338. Cambridge, MA: The MIT Press.

Sogbedji, J.M., H.M. Van Es, and C.L. Yang. 2000. Nitrate leaching and nitrogen budget as affected by maize nitrogen rate and soil type. *Journal of Environment Quality* 29: 1813–1820.

Su, F., X.Q. Ding, Z.L. Gao, B.X. Huang, X.P. Chen, F.S. Zhang, K. Martin, and V. Römheld. 2007. Ammonia volatilization from nitrogen fertilization of winter wheat-summer maize rotation system in the North China Plain. *China Environmental Science* 27: 409–413. (in Chinese with English abstract.).

Sun, H.Y., C.M. Liu, X.Y. Zhang, Y.J. Shen, and Y.Q. Zhang. 2006. Effects of irrigation on water balance, yield and WUE of winter wheat in the North China Plain. *Agricultural Water Management* 85: 211–218.

Tilman, D., K.G. Cassman, P.A. Matson, R. Naylor, and S. Polasky. 2002. Agricultural sustainability and intensive production practices. *Nature* 418: 671–678.

Tong, T.A., O. Emteryd, and S.L. Zhang. 2004. Evaluation of over-application of nitrogen fertilizer in China's Shanxi province.

Scientia Agricultura Sinica 37: 1239–1244. (in Chinese with English abstract).

Wang, J.Q. 2007. *Analysis and evaluation of yield increase of fertilization and nutrient utilization efficiency for major cereal crops in China*. PhD Thesis, China Agricultural University, Beijing, China (in Chinese with English summary).

Wang, H., L. Zhang, W.R. Dawes, and C. Liu. 2001. Improving water use efficiency of irrigated crops in the North China Plain—Measurements and modeling. *Agricultural Water Management* 48: 151–167.

Welch, L.F., D.L. Mulvaney, M.G. Oldham, L.V. Boone, and J.W. Pendleton. 1971. Corn yields with fall, spring, and sidedress nitrogen. *Agronomy Journal* 63: 119–123.

Yuan, F.M., Z.M. Chen, Z.H. Yao, C.S. Zhou, G.M. Fu, Y.L. Song, and X.P. Li. 1995. Transformation, accumulation and leaching loss of nitrate-N in surface layer of an Fluvo-Aquic soil. *Acta Pedologica Sinica* 32: 388–399. (in Chinese with English abstract.).

Zhang, S.L., G.X. Cai, X.Z. Wang, Y.H. Xu, Z.L. Zhu, and J.R. Freney. 1992. Loss of urea-nitrogen applied to maize grown on a calcareous fluvo-aquic soil in North China Plain. *Pedosphere* 2: 171–178.

Zhang, Y.M., C.S. Hu, and X.X. Dong. 2005. Ammonia volatilization from wheat-maize rotation field in the piedmont of Taihang. *Plant Nutrition and Fertilizer Science* 11: 417–419. (in Chinese with English abstract.).

Zhang, F.S., X.R. Wang, X.T. Ju, W.Q. Ma, Q.J. Wang, and C.L. Kou. 2002. Spatial and temporal variation of nitrogen, phosphorus and potassium, and fertilization recommendation. In *Integrated nutrient management*, ed. F.S. Zhang, and R.F. Jiang, 79–87. Beijing: China Agricultural University Press. (in Chinese).

Zhang, F.S., J.Q. Wang, W.F. Zhang, Z.L. Cui, W.Q. Ma, X.P. Chen, and R.F. Jiang. 2008. Nutrient use efficiencies of major cereal crops in china and measures for improvement. *Acta Pedologica Sinica* 45: 915–924. (in Chinese with English abstract).

Zhao, J.R. 1997. The investigation and analysis of N application and yield in Beijing suburb. *Beijing Agricultural Science* 15: 36–38. (in Chinese).

Zhao, R.F. 2006. *The sustainability evaluation of the optimized management of water and nitrogen resources for winter wheat-summer maize rotation system*. PhD Thesis, China Agricultural University, Beijing, China (in Chinese with English summary).

Zhao, R.F., X.P. Chen, and F.S. Zhang. 2006. Fertilization and nitrogen balance in a wheat–maize rotation system in North China. *Agronomy Journal* 98: 938–945.

Zhu, Z.L. 1998. The present situation of nitrogen fertilizer use, and the problems and strategies in China. In *Fertilizer problems in sustainable development of agriculture in China*, ed. Q.K. Li, Z.L. Zhu, and T.R. Yu, 38–51. Nanchang: Jiangxi Science and Technology Publishers. (in Chinese).

Zhu, Z.L., and D.L. Chen. 2002. Nitrogen fertilizer use in China–Contributions to food production, impacts on the environment and best management strategies. *Nutrient Cycling in Agroecosystems* 63: 117–127.

Zhu, Z.L., and Q.X. Wen. 1992. *Soil nitrogen in Chinese*. Nanjing: Jiangsu Science and technique publisher. (in Chinese).

AUTHOR BIOGRAPHIES

Zhenling Cui is associate professor at the Department of Plant Nutrition, College of Resources and Environmental Sciences, China Agricultural University, Beijing, 100193, China.
Address: Department of Plant Nutrition, College of Resource and Environmental Sciences, China Agricultural University, Beijing 100094, China.

Xinping Chen is professor at the Department of Plant Nutrition, College of Resources and Environmental Sciences, China Agricultural University, Beijing, 100193, China.
Address: Department of Plant Nutrition, College of Resource and Environmental Sciences, China Agricultural University, Beijing 100094, China.

Fusuo Zhang (✉) is professor at the Department of Plant Nutrition, College of Resources and Environmental Sciences, China Agricultural University, Beijing, 100193, China.
Address: Department of Plant Nutrition, College of Resource and Environmental Sciences, China Agricultural University, Beijing 100094, China.
e-mail: zhangfs@cau.edu.cn