Improved Nitrogen Management for an Intensive Winter Wheat/Summer Maize Double-cropping System

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Improving N and straw management to achieve high crop yields, minimize nitrate leaching, and balance soil fertility presents challenges in winter wheat (*Triticum aestivum* L.)/summer maize (*Zea mays* L.) double cropping systems on the North China Plain. A long-term field experiment was designed to study crop performance, nitrate leaching, and N balance under three N management approaches (conventional farming practice, improved N_{min}, and N balance methods) with two straw management options (straw removal and return), and two types of organic amendment (cattle [*Bos taurus*] manure and municipal waste compost). Grain and straw yields and C/N ratios were determined in each crop, together with N uptake and residual NO_3–N in the top 2 m of the soil profile. Over six successive crops of the study (October 2006–September 2009) 32 to 93% of applied N was saved without reducing either wheat or maize yields and less NO_3–N accumulated in the top 1 m of the soil (the root zone) or leached 1 to 2 m down the soil profile when the two new N management approaches were used in comparison with conventional N management. Straw return did not affect crop yield or NO_3–N accumulation but the N rate with straw return in the improved N_{min} method increased due to N immobilization induced by the straw. Moreover, in the hot and wet maize seasons, chemical fertilizer N rate in the N balance method can further decrease by reducing the target residual NO_3–N in the 0 to 1 m root zone and by increasing the percentage availability of total N in organic amendments in future studies.

Abbreviations: M_{bal}, cattle manure with nitrogen balance method; N_{con}, conventional farming practice; N_{min}, improved N_{min} test; N_0, control; W_{bal}, waste compost with nitrogen balance method.

Management of N and straw presents challenges for combining high crop yields, environmental protection, and improved soil fertility in winter wheat/summer maize cropping systems on the North China Plain (Ju et al., 2009). Excessive use of N fertilizer in pursuit of high crop yields in this intensively managed double-cropping system has resulted in adverse environmental effects including leaching of NO_3^- to the shallow groundwater and emission of the greenhouse gas N_2O (Ju et al., 2011). It has been reported that the average fertilizer N application rate exceeds 300 kg N ha^{-1} for winter wheat and 250 kg N ha^{-1} for summer maize (Zhao et al., 2006; Cui et al., 2008a) in conventional farming practice and the residual NO_3–N after maize harvest in this region was 275 kg N ha^{-1} in the top 90 cm and 213 kg N ha^{-1} between 90- and 180-cm soil depth (Ju et al., 2006). An understanding of N balance in the soil–crop system is therefore essential for the development of more sustainable fertilizer management strategies.

The soil N_{min} test (NO_3–N + NH_4–N) method provides a useful tool for determining the N fertilizer rate (Wehrmann et al., 1988) based on the difference

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between "N demand for target yield" and soil N_{min} storage in the root zone. An improved N_{min} method for synchronizing crop N uptake and N supply from soil and fertilizer was established and used successfully on the North China Plain by Chen et al. (2006) and Cui et al. (2008b, 2008c) who applied chemical N fertilizer two or three times during the growing season according to the target N demand of the crop minus soil NO_3–N storage in the root zone at different growth stages. This method did not include soil NH_4–N due to its constantly low concentration during the growing season (Ju et al., 2004). Using this method 79% of N fertilizer was saved over eight successive seasons of the winter wheat/summer maize cropping system without any decrease in crop yields compared with conventional N application (Zhao et al., 2006). However, the method still needs to be tested with different straw management options and manure applications.

Historically, crop residues were widely used on the North China plain as fuel and fodder. This practice has changed during the last decade and farmers return more residues to their fields (Huang and Sun, 2006; Liu et al., 2006). These changing practices will likely affect N management because N transformations in soil are closely linked to the C cycle. All active heterotrophic microorganisms simultaneously assimilate C and N during the decomposition of crop residues or soil organic matter (Green et al., 1995). An understanding of this linkage is important, for example for determining how changes in N fertilization practices affect the soil organic matter pool. Straw mulching can also increase the retention of soil water, decrease moisture evaporation, intercept the direct effects of raindrops (Blanco-Canqui and Lal, 2007) and postpone NO_3–N leaching with rain infiltration. Long-term straw incorporation can increase microbial activity and soil organic C and N (Cassman et al., 1996) and further improve the potential N supply of the soil. The C/N ratio of straw is a key factor determining the N mineralization–immobilization cycle in soil. A low C/N ratio (<20:1) will promote net N mineralization (Stevenson and Cole, 1999) and a higher C/N ratio (>30:1) will lead to transient competition for N between soil microorganisms and crops with a corresponding decrease in crop production. It is therefore necessary to integrate the higher C/N ratio of straw with chemical N fertilizer to improve soil fertility and maintain crop production. The joint management of fertilizer N with straw or manure still presents problems in the quest for high crop yields, environmental protection, and improvements in soil fertility in winter wheat/summer maize cropping systems in this region.

Application of solid manures and municipal waste composts to farmland is the primary method of recycling nutrients and reducing pollution. Organic amendments are generally incorporated into soils with tillage because surface application of organic animal manures and municipal composts can generate substantial NH_3 volatilization and decrease the efficiency of organic sources of N (Fenn and Hossner, 1985; Mattila, 1998). How to evaluate the availability of manure N to the current crop and subsequent crops is still a difficult question that needs to be answered if reliable N recommendations are to be developed for the North China Plain. Over-use of chemical fertilizer N frequently occurs in agriculture because the N supplied by organic manures is usually not taken into account (He et al., 2007). Choudhary et al. (1996) reported that 45% of pig (*Sus scrofa*) manure was mineralized in the first year after application and Sikora and Szmidt (2001) found that about 25% of compost N was released in the first year and 10% in each subsequent year. The N balance approach was introduced by Klausner and Guest (1981) based on the properties of organic fertilizers. The method assumes that N uptake by crops matches the amount of available N applied as fertilizer or manure (Motavalli et al., 1989) and the available N in manure is closely correlated with the percentage of total N in applied manure. However, this N balance approach still does not include soil N supply, especially on the North China Plain with the high potential of nitrification and mineralization (Ju et al., 2009). In view of input–output relationship in a crop season N management strategy, the balance approach should also consider pre-plant and target postharvest soil NO_3–N storage in root zone, and this N balance approach has not yet been evaluated in the double cropping systems on the North China Plain, especially when combined with straw return and additional N fertilizer application to achieve high crop yields.

The objective of the present study was to evaluate crop performance, NO_3–N accumulation in the root zone and leaching, and N balance when using (i) the improved N_{min} method with straw removal or return or (ii) the N balance method basing on application of solid cattle manure or municipal waste compost with straw return in comparison with (iii) the conventional farming practice. A second objective was to evaluate the suitability of the parameters for calculating fertilizer N rate with the improved N_{min} and N balance methods and their fertilizer N saving potential compared with conventional methods.

MATERIALS AND METHODS

Site

The continuing long-term field experiment started in October 2006 at the Shangzhuang Research Station (39°48′ N, 116°28′ E; 40 m above sea level) of China Agricultural University in suburban Beijing (Fig. 1). Weather at the site is typical of a continental monsoon climate. Annual precipitation is 500 to 700 mm with 60 to 70% of the rainfall occurring during summer (July–September) and the annual cumulative mean temperature for days with mean temperatures above 10°C is 4000 to 5000°C and the annual frost-free period is 175 to 220 d. In the first 3 yr of the present study the precipitation was 450, 768, and 340 mm during the periods October 2006 to September 2007, October 2007 to September 2008 and October 2008 to September 2009, respectively. The corresponding average temperatures were 11.3 11.5 and 11.3°C. Precipitation and average temperature details for each month during this period together with the average precipitation and temperature per month since 1998 are shown in Fig. 2a and 2b. In terms of precipitation, the 3 yr represented normal, wet, and dry conditions.

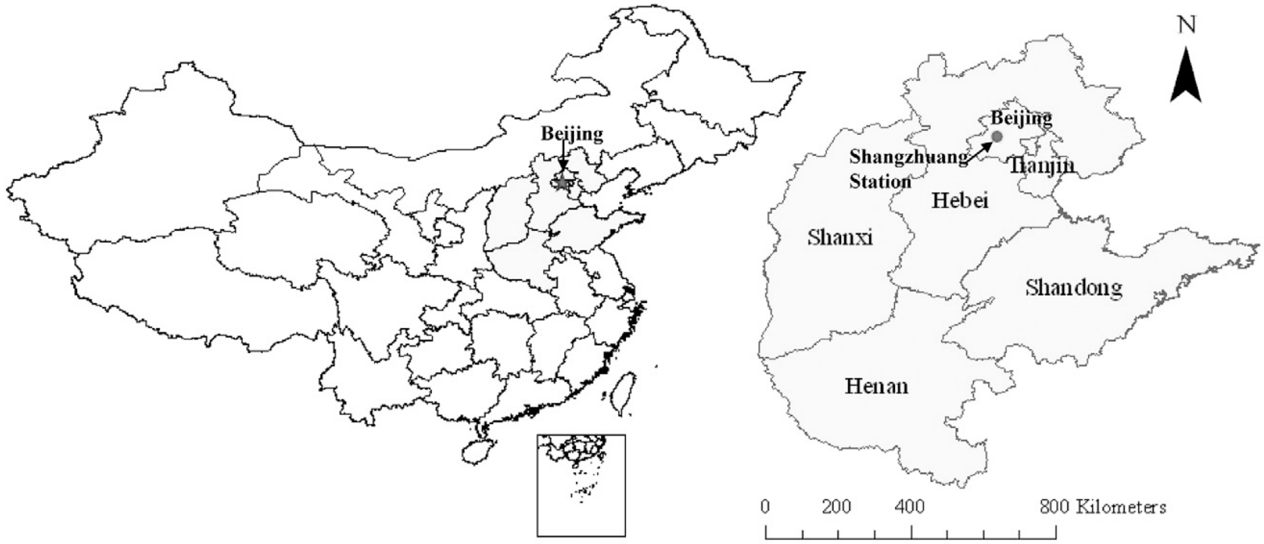

Fig. 1. Location of Shangzhuang station in Beijing on the North China Plain.

The typical cropping system on the North China Plain consists of winter wheat sown at the beginning of October and harvested in the middle of June of the following year followed by summer maize sown in the middle of June and harvested at the end of September. The area has a calcareous alluvial soil with silty texture and the soil type is Calcareous Cambisol (FAO, 2002). The plow layer (top 20 cm) of the soil profile has a clay content of 28%, pH of 8.1 (1:2.5, soil/water), organic matter 13.3 g kg^{-1}, total N 0.8 g kg^{-1}, NO_3–N 24.5 mg kg^{-1}, NH_4–N 1.20 mg kg^{-1}, $NaHCO_3$–extractable P 7.8 mg kg^{-1}, and NH_4OAc-extractable K 76.2 mg kg^{-1}. Soil bulk density is 1.31, 1.47 and 1.45 g cm^{-3} at depths of 0 to 20, 20 to 40, and below 40 cm. From the middle of June to the end of September 2006, summer maize was grown without any fertilizer application to make the field uniform in preparation for the long-term experiment. Before the sowing of wheat in October 2006, residual NO_3–N at 0 to 1 m and 1 to 2 m soil depths was 171.8 and 116.8 kg N ha^{-1}, respectively; the values used to calculate the N balance among the treatments.

Experimental Design

The experimental design was a randomized complete block with three replications and the plot size was 8 × 8 m. There were eight treatments comprising three levels of N application (zero-N control, conventional practice, and soil N_{min} test), each with two levels of straw management (straw removal and return) plus two types of organic amendment (cattle manure and municipal waste compost, both with straw return) (Table 1). Winter wheat received two applications of N fertilizer, basal and topdressed. In the conventional farming practice treatments (N_{con} and N_{con}+C) and C represents straw return, N rate followed typical farming practices on the North China Plain, that is, 150 kg N ha^{-1} before plowing for seed-bed preparation, and 150 kg N ha^{-1} at regreening-jointing stage. In the improved N_{min} test treatments (N_{min} and N_{min}+C), N rates were based on the synchronization of crop N demand and soil N supply (Chen et al., 2006; Zhao et al., 2006), that is, the target crop N demand minus NO_3–N in the root zone. The target crop N demands for basal application and topdressing were 100 and 200 kg N ha^{-1}, and the corresponding root zone depths were 0 to 40 cm and 0 to 100cm (Chen et al., 2006; Zhao et al., 2006). In the manure and compost treatments (M_{bal}+C and W_{bal}+C), the fertilizer N rate was based on the N balance calculation, that is, N output minus N input over the whole crop growing season with one-third of the N applied as a basal and two-thirds as a topdressing

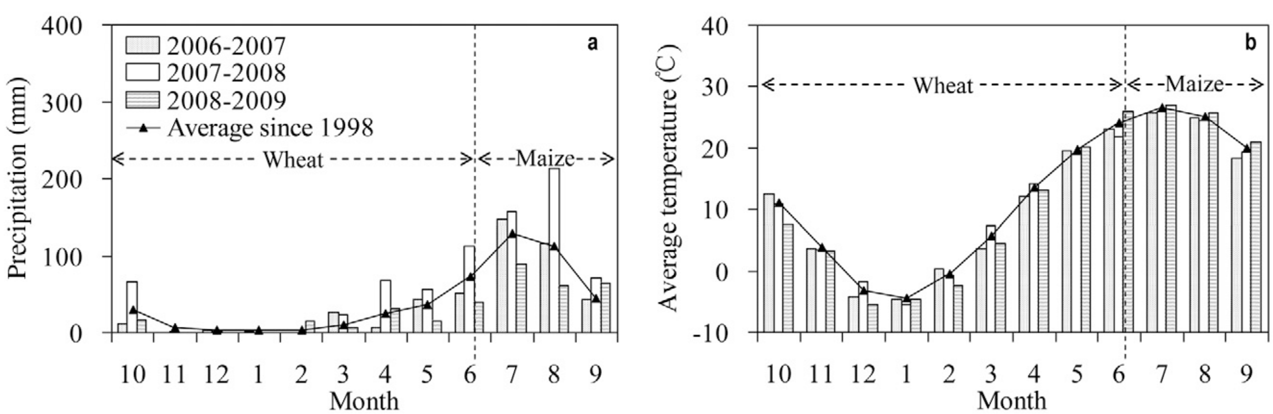

Fig. 2. (a) Precipitation and (b) average temperature from October 2006 to October 2009 at Shangzhuang station.

Table 1. Treatments applied in the long-term field experiment.

Code†	Treatment	Nitrogen management approach
N_0	Control, no N application, wheat and maize straw removed	No N application
N_0+C	Control, no N application, wheat straw mulching and maize straw returned	
N_{con}	Conventional chemical fertilizer N application, wheat and maize straw removed	Conventional farming practice
N_{con}+C	Conventional chemical fertilizer N application, wheat straw mulching and maize straw returned	
N_{min}	Chemical fertilizer N application according to N_{min} test, wheat and maize straw removed	Improved N_{min} test
N_{min}+C	Chemical fertilizer N application according to N_{min} test, wheat straw mulching and maize straw returned	
M_{bal}+C	Composted cattle manure, wheat straw mulching, and maize straw returned, supplementary chemical fertilizer N according to N balance calculation	N balance method
W_{bal}+C	Composted municipal waste, wheat straw mulching, and maize straw returned, supplementary chemical fertilizer N according to N balance calculation	

† N_0, N_{min}, N_{con}, M_{bal}, and W_{bal} represent control, improved N_{min} test, conventional farming practice, cattle manure with nitrogen balance method, waste compost with nitrogen balance method; C represents straw return.

application. The N outputs included total N uptake by the aboveground parts of wheat and the target residual NO_3–N in the root zone (0–100 cm) after the wheat harvest. Total N uptake was assumed to be 180 kg N ha^{-1} in this region according to work reported by Chen et al. (2006) and Zhao et al. (2006) and target residual NO_3–N was assumed to be 100 kg N ha^{-1} (Cui et al., 2008d). The N inputs included an assumed 40% of total N as available N in the organic amendments in the current wheat season (National Extension Center of Agriculture Technique in China, 1999; Williams and Hall, 1986; Huang, 1994; Beegle et al., 2008; Sims and Stehouwer, 2008) and residual NO_3–N in the 0- to 100-cm root zone before sowing of wheat.

The methods for calculating fertilizer N application rates for summer maize were similar to those for winter wheat. In all treatments the N fertilizer was applied twice, that is, at the 4th and 10th leaf stages. The conventional farming practice treatments used N application rates typical for the region, that is, 130 kg N ha^{-1} at both the 4th leaf and 10th leaf stages. In the improved N_{min} test treatments the target crop N demand was 100 kg N ha^{-1} for the fourth leaf stage and 160 kg N ha^{-1} at the 10th leaf stage and the corresponding root zones were 0 to 60 cm and 0 to 100 cm depths, as recommended by Zhao et al. (2006) and based on soil texture at Shangzhuang station. In the organic amendment treatments, N output minus N input was calculated during the whole crop growing season and divided into two halves for the 4th and 10th leaf stages. Total N uptake by aboveground maize was assumed to be 160 kg N ha^{-1} and 20% postavailable N from organic fertilizer (applied during the previous wheat season) was added to the calculation of N input in the current maize season (National Extension Center of Agriculture Technique in China, 1999; Williams and Hall, 1986; Shen et al., 2000; Beegle et al., 2008; Sims and Stehouwer, 2008). Other details of N output and input were the same as in the wheat season. Due to the continuous cultivation of winter wheat and summer maize, the pre-plant soil NO_3–N was used regarding the postharvest NO_3–N in the 0- to 100-cm soil profile after each crop harvested as the soil NO_3–N input in the N balance method. The details of N rates in each treatment from October 2006 to September 2009 are listed in Table 2.

The row spacing of winter wheat (variety Nongda 211) was 15 cm and the seeding rate was 225 kg ha^{-1}. The distances in summer maize (variety Zhengdan 958) between rows and plants were 60 and 25 cm, respectively. Fertilizer P and K and organic fertilizer were applied as basal dressings only in the winter wheat season at rates of 160 kg ha^{-1}yr^{-1} P_2O_5, 90 kg ha^{-1} yr^{-1} K_2O and 30 t ha^{-1} yr^{-1} fresh organic fertilizer. Moisture content of the organic fertilizer was determined by weighing a subsample before and after oven drying at 60°C. Kjeldahl N concentrations of dry solid cattle manure were 4.3 (a mixture of matured forage and composted cattle manure), 12.7 and 18.4 g kg^{-1} for the years 2006, 2007, and 2008 and corresponding values of dry municipal waste compost were 6.4, 10.4 and 8.6 g kg^{-1}.

Field Management

In the winter wheat seasons inorganic fertilizers, organic amendments, and machine-crushed maize straw were incorporated into the soil with tractor-plowed tillage (20–25-cm depth) at the beginning of October each year, and the topdressing inorganic N fertilizer was broadcast just before regreening-jointing irrigation. In the summer maize season N fertilizer was broadcast at the 4th and 10th leaf maize stage just before the next precipitation event or supplementary irrigation, and the crushed wheat straw was mulched on the soil surface after the wheat harvest in the middle of June each year. Both maize and wheat straw were crushed to 5 to 8 cm using mechanical equipment.

Winter wheat was irrigated on 20 November (before the winter freeze) in the sowing year and on 4 April (regreening-jointing), 7 May (heading), and 22 May (filling) in the following year. The quantities of irrigation were 600, 700, 600, and 0 m^3 ha^{-1} in the 2006–2007 wheat season, 600, 500, 0, and 700 m^3 ha^{-1} in the 2007–2008 wheat season and 600, 600, 600, and 600 m^3 ha^{-1} in the 2008–2009 wheat season, respectively; the irrigation was generally 600 m^3 ha^{-1} with 100 m^3 ha^{-1} fluctuation according to the precipitation during different growth stages of wheat. Pesticide (a mixture of dichlorovos and dimethoate) was sprayed in the middle of April and the middle or end of May, mainly to control aphids, and weeds were removed by hand in the middle of April.

Table 2. Amount and timing of fertilizer N application (kg N ha^{-1}) in winter wheat and summer maize seasons from October 2006 to September 2009.

Code†	Basal N (B) and topdressing N (T) for winter wheat 2006–2007 B	2006–2007 T	2007–2008 B	2007–2008 T	2008–2009 B	2008–2009 T	Avg. of three wheat seasons	N added at the fourth leaf (4th) and 10th leaf (10th) stage for summer maize 2007 4th	2007 10th	2008 4th	2008 10th	2009 4th	2009 10th	Avg. of three maize seasons
N_0	0.0	0.0	0.0	0.0	0.0	0.0	0.0 ± 0.0‡	0.0	0.0	0.0	0.0	0.0	0.0	0.0 ± 0.0
N_0+C	0.0	0.0	0.0	0.0	0.0	0.0	0.0 ± 0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0 ± 0.0
N_{con}	150	150	150	150	150	150	300.0 ± 0.0	130	130	130	130	130	130	260.0 ± 0.0
N_{con}+C	150	150	150	150	150	150	300.0 ± 0.0	130	130	130	130	130	130	260.0 ± 0.0
N_{min}	86.0	0.0	65.0	74.0	82.4	45.0	117.5 ± 13.1	0.0	45.0	66.7	65.2	85.1	45.0	102.3 ± 23.4
N_{min}+C	86.0	39.6	78.3	102.9	69.0	45.0	140.3 ± 16.9	60.8	78.3	58.2	92.4	87.2	45.0	140.6 ± 4.4
M_{bal}+C§	21.5	42.9	0.0	0.0	0.0	0.0	21.5 ± 17.5	69.5	69.5	83.0	83.0	94.0	94.0	164.3 ± 11.6
W_{bal}+C§	14.9	29.7	20.9	41.9	31.8	63.5	67.6 ± 12.1	69.9	69.9	97.3	97.3	96.5	96.5	175.8 ± 14.7

† N_0, N_{min}, N_{con}, M_{bal}, and W_{bal} represent control, improved N_{min} test, conventional farming practice, cattle manure with nitrogen balance method, waste compost with nitrogen balance method; C represents straw return.

‡ Number represents mean ± standard error.

§ The data are chemical fertilizer N rates. In M_{bal}+C treatment the calculated N amount from cattle manure for wheat from 2006 to 2008 was 44, 114, and 91 kg N ha^{-1}, respectively; that for maize was 22, 57, and 46 kg N ha^{-1}, respectively. Correspondingly, N from compost waste in W_{bal}+C treatment was 63, 70, and 78 kg N ha^{-1} for wheat and 32, 35, and 39 kg N ha^{-1} for maize.

Similarly, the seedling irrigation of summer maize was at the beginning of July and the amount of irrigation was 500 m^3 ha^{-1} in 2007, 600 m^3 ha^{-1} in 2009, and no irrigation in 2008 because of heavy rain. To protect maize seedling from pest damage, the same pesticide mixture and a herbicide (acetochlor) were sprayed as soon as summer maize was sown; and the liquid pesticide mixture was applied again at the beginning of July. A solid granular pesticide (carbofuran) was applied to the top leaves of summer maize to avoid pest damage to maize at the beginning of August. Residual weeds were removed by hand at the beginning of July and August. On 31 Aug. 2009 all of the maize at the filling stage (except for the control treatments) had lodged due to strong winds.

Plant Measurements

At the winter wheat harvest fresh aboveground biomass was harvested from an area in the middle of each plot that measured 9 m^2 (3 × 3 m). Grain and straw samples were oven-dried at 60°C for the determination of dry matter yield. At the summer maize harvest 14.4 m^2 (six rows 4 m in length) in the middle of each plot were harvested to determine fresh ear and stover yields together with ear number. Five plants were randomly selected from the harvested summer maize and separated into grain, cob, and stover to determine the oven-dried weight at 60°C. The grain yield of maize was calculated by deduction of cob yield. The C and N contents of straw and grain for both wheat and maize were determined using a CN analyzer (Vario Max CN, Elementar, Hanau, Germany). Crude protein of grain was calculated by multiplying the grain N concentration by 5.83 for wheat and 6.25 for maize.

Soil Measurements

Soil samples were taken from the top 200 cm of the soil profile in each plot after harvest. Soil cores were collected from two points in each plot, separated into 20-cm depth intervals, mixed thoroughly to obtain composite samples from each depth layer, placed in labeled plastic bags, sealed, and stored frozen before analysis for NO_3–N in the laboratory. Each fresh soil sample was sieved with a 3 mm mesh and extracted with 0.01 M $CaCl_2$ at a soil/water ratio of 1:10 (W/V) to determine the concentrations of NO_3–N using a continuous flow analyzer (TRAACS 2000, Bran and Luebbe, Norderstedt, Germany). The NO_3–N at 0 to 1 and 1 to 2 m in the soil profile was calculated after each harvest to investigate NO_3–N accumulation and leaching, respectively.

Calculation of Nitrogen Balance

The calculated N balance for each crop can be used to evaluate the surplus or deficit relationship between total N input and total N output and to further illustrate total N losses or NO_3–N accumulation. The N balance was estimated by apparent N mineralization (Meisinger, 1984; Zhao et al., 2006) and apparent N loss (Ma et al., 1999; Zhao et al., 2006). The apparent N mineralization and N loss was calculated using the following equations:

$$\text{Apparent N mineralization} = N_{uptake} + NO_3\text{–}N_{post} - NO_3\text{–}N_{previous}$$

$$\text{Apparent N loss} = N_{fertilizer} + \text{Apparent N mineralization} + NO_3\text{–}N_{previous} - N_{uptake} - NO_3\text{–}N_{post}$$

$$N_{uptake} = \text{Grain N concentration} \times \text{Grain yield} + \text{Straw N concentration} \times \text{Straw yield}$$

where apparent N mineralization is calculated in the control treatment, apparent N loss calculated in the N application treatments; N_{uptake} is N uptake by aboveground parts at crop harvest, NO_3–N_{post} is residual NO_3–N in 0- to100-cm soil depth after current crop harvest, and NO_3–$N_{previous}$ is residual NO_3–N in 0- to 100-cm soil depth after the previous crop harvest. The calculated available N amount from organic fertilizer in each crop was also taken into account in the N fertilizer application (National Extension Center of Agriculture

Table 3. Crop yield (t ha^{-1}) after each crop harvest from 2007 to 2009.

Code†	Wheat (n = 3)			Maize (n = 3)			Annual (Wheat+Maize) (n = 3)			N management (n = 18)		
	2007	2008	2009	2007	2008	2009	2007	2008	2009	Wheat	Maize	Annual
N_0	4.5 ± 0.12‡d§	5.0 ± 0.51b	2.2 ± 0.04c	5.9 ± 0.69c	4.7 ± 0.30c	4.1 ± 0.13b	10.3 ± 0.61c	9.7 ± 0.53 c	6.3 ± 0.16 b	3.9 ± 0.32b	4.9 ± 0.28b	8.9 ± 0.50b
N_0+C	4.6 ± 0.06cd	5.2 ± 0.33b	2.2 ± 0.09c	6.7 ± 0.15bc	4.4 ± 0.28c	3.8 ± 0.18b	11.3 ± 0.09c	9.6 ± 0.35 c	6.0 ± 0.24 b			
N_{con}	4.9 ± 0.10bcd	6.4 ± 0.06a	5.4 ± 0.10ab	7.9 ± 0.09ab	7.8 ± 0.30b	5.2 ± 0.10a	12.8 ± 0.06b	14.1 ± 0.27b	10.6 ± 0.16a	5.6 ± 0.12a	7.3 ± 0.33a	12.9 ± 0.36a
N_{con}+C	5.3 ± 0.16ab	5.9 ± 0.10ab	5.7 ± 0.10a	8.5 ± 0.38a	8.6 ± 0.32ab	5.8 ± 0.30a	13.9 ± 0.53ab	14.5 ± 0.34ab	11.6 ± 0.39a			
N_{min}	5.2 ± 0.09abc	6.4 ± 0.06a	5.2 ± 0.13ab	7.5 ± 0.48ab	8.5 ± 0.42ab	5.1 ± 0.32a	12.7 ± 0.44b	14.9 ± 0.36ab	10.7 ± 0.43a	5.8 ± 0.15a	7.1 ± 0.36a	12.9 ± 0.46a
N_{min}+C	5.5 ± 0.13a	6.8 ± 0.20a	5.4 ± 0.14ab	8.2 ± 0.26a	8.3 ± 0.29ab	5.2 ± 0.09a	13.7 ± 0.34ab	15.1 ± 0.42ab	10.6 ± 0.15a			
M_{bal}+C	5.5 ± 0.23a	6.5 ± 0.29a	5.1 ± 0.26b	8.6 ± 0.10a	9.0 ± 0.33a	5.2 ± 0.06a	14.1 ± 0.27a	15.6 ± 0.15a	10.3 ± 0.21a	5.7 ± 0.72a	7.6 ± 0.39a	13.3 ± 0.51a
W_{bal}+C	5.4 ± 0.22ab	6.5 ± 0.16a	5.3 ± 0.31ab	7.9 ± 0.24ab	9.0 ± 0.16a	5.7 ± 0.59a	13.3 ± 0.03ab	15.5 ± 0.11a	11.1 ± 0.86a			
Avg.¶ (n = 18)	5.3 ± 0.08b	6.4 ± 0.09a	5.4 ± 0.09b	8.1 ± 0.15a	8.5 ± 0.16a	5.4 ± 0.14b	13.4 ± 0.19b	15.0 ± 0.17a	10.8 ± 0.21 c			

† N_0, N_{min}, N_{con}, M_{bal}, and W_{bal} represent control, improved N_{min} test, conventional farming practice, cattle manure with nitrogen balance method, waste compost with nitrogen balance method; C represents straw return.

‡ Number represents mean ± standard error.

§ Means with the same lowercase are not significantly different in the same year (column) among eight treatments; in the same crop (columns) among four N management regimes; and in the same crop ("Avg." row) among 3 yr (P < 0.05).

¶ Mean of the above six N application treatments, not including N_0 and N_0+C treatments.

Technique in China, 1999). The apparent N loss in straw removal treatments used the value of apparent N mineralization in N_0 treatment; correspondingly, straw return treatments used the value in N_0+C treatment.

Statistical Analysis

Data are expressed on oven-dried plant or soil basis. One-way analysis of variance was conducted using the SPSS version 11.0 software package and the mean values were compared using least significant difference (LSD) at the 5% level. Data are presented as mean ± one standard error of the mean (SEM).

RESULTS

Determining Fertilizer Nitrogen Rate by Different Approaches

The improved N_{min} (N_{min}, N_{min}+C) and N balance (M_{bal}+C, W_{bal}+C) methods greatly reduced fertilizer N inputs to both crop species (Table 2) compared to conventional farming practice (N_{con}, N_{con}+C). In the case of winter wheat, N_{min} and N_{min}+C saved 61 and 53% fertilizer N, and M_{bal}+C and W_{bal}+C saved 93 and 77%, respectively. The corresponding savings for summer maize were 61, 45, 37, and 32%. The M_{bal}+C and W_{bal}+C treatments in wheat gave the largest savings of fertilizer N input because 40% of total N in the organic amendments was assumed to be in an available form, and in maize gave the lowest savings because of assumed NO_3–N depletion by the preceding wheat crop and the underestimated mineralization of manure or compost in hot and wet summer. Environmental impacts may therefore be greatly reduced by these N recommendation methods.

Grain Yield and Nitrogen Uptake by Crop Aboveground

More than six successive crops in 3 yr (taking both wheat and maize together) the average grain yield (n = 18) did not differ significantly (P > 0.05) among the different N management approaches except for the control treatments (N_0 and N_0+C) (Table 3), although the improved N_{min} and N balance methods gave considerable savings of fertilizer N (Table 2). Straw return and manure application did not give a significant yield increase in either crop (P > 0.05). In 2008 the average grain yield of wheat was higher because of the favorable precipitation from April to June (Fig. 2a) and in 2009 that of maize was lower because of lodging in strong winds at the end of August, a high risk when maize is planted at high density. Annual grain yields in this region can be maintained at around 13 t ha^{-1} under normal climatic conditions, but fertilizer N rates may be substantially reduced using the improved N_{min} or N balance method compared to conventional farming practice. The gradual decrease in grain yields of both crops in the control treatments suggests depletion of NO_3–N and the inability of mineralization of soil organic N to meet crop N requirements.

Average N uptake by wheat or maize (n = 18) in the treatments representing conventional farming practice was higher than using the improved N_{min} or N balance treatments (Table 4) and reached significance (P < 0.05) in the winter

Table 4. Nitrogen uptake (kg N ha^{-1}) by aboveground parts after each harvest from 2007 to 2009.

Code†	Wheat (*n* = 3)			Maize (*n* = 3)			N management (*n* = 18)	
	2007	2008	2009	2007	2008	2009	Wheat	Maize
N_0	141.7 ± 2.4‡c§	123.8 ± 16.4c	69.3 ± 3.2c	123.1 ± 14.6e	117.2 ± 6.3b	89.8 ± 4.7b	112.3 ± 8.4c	107.5 ± 6.4b
N_0+C	141.1 ± 9.9c	132.4 ± 9.6c	65.3 ± 1.5c	138.1 ± 12.7de	83.6 ± 11.9b	93.3 ± 9.9b		
N_{con}	199.2 ± 9.9ab	196.3 ± 5.0ab	200.9 ± 0.8ab	183.4 ± 2.3abc	214.7 ± 25.5a	159.7 ± 1.1a	209.4 ± 4.2a	187.5 ± 6.8a
N_{con}+C	213.4 ± 12.4a	219.0 ± 4.8a	227.6 ± 8.3a	205.4 ± 7.4a	186.8 ± 15.5a	174.8 ± 5.1a		
N_{min}	180.8 ± 4.5b	197.9 ± 8.3ab	190.0 ± 2.5b	158.2 ± 6.0cd	212.2 ± 20.8a	155.8 ± 12.0a	186.5 ± 3.3b	173.7 ± 7.6a
N_{min}+C	178.4 ± 3.3b	188.5 ± 2.8ab	183.6 ± 14.3b	152.7 ± 1.8d	207.1 ± 11.6a	156.4 ± 4.6a		
M_{bal}+C	194.3 ± 9.6ab	185.9 ± 7.9b	180.6 ± 7.9b	187.9 ± 4.1ab	225.2 ± 16.3a	160.1 ± 4.9a	184.2 ± 3.6b	184.8 ± 7.0a
W_{bal}+C	186.9 ± 5.1ab	177.7 ± 6.4b	179.6 ± 10.5b	166.9 ± 3.7bcd	207.5 ± 14.2a	161.3 ± 7.1a		
Avg.¶ (*n* = 18)	192.2 ± 4.4a	194.2 ± 4.0a	193.7 ± 5.3a	175.8 ± 4.7b	208.9 ± 7.8a	161.3 ± 3.1b		

† N_0, N_{min}, N_{con}, M_{bal}, and W_{bal} represent control, improved N_{min} test, conventional farming practice, cattle manure with nitrogen balance method, waste compost with nitrogen balance method; C represents straw return.

‡ Number represents mean ± standard error.

§ Means with the same lowercase letter are not significantly different in the same year (columns) among eight treatments; in the same crop (columns) among 4 N management regimes; and in the same crop ("Avg." row) among 3 yr ($P < 0.05$).

¶ Mean of above six N application treatments, not including N_0 and N_0+C treatments.

wheat season but not in the summer maize season. This may be attributed to high N concentrations of straw and grain in conventional treatments (data not shown) although the yield of straw or grain was not significantly higher in these treatments as mentioned above. Straw return did not increase N uptake in any of the three N application treatments, but one interesting observation was that N uptake in N_{con}+C treatments was generally higher than that in N_{con} treatments, and N uptake in N_{min} treatments higher than in N_{min}+C treatments. This may reflect a reduction in N supply to crops in N_{min}+C treatments due to soil N immobilization. However, N immobilization with straw return in the treatments with excessive fertilizer N application (N_{con}+C) increased crop N uptake through luxury N supply. Average N uptake showed some year-to-year variation in both crops but this was not significant except for maize in 2009 which was affected by lodging as described above.

Carbon/Nitrogen Ratio of Straw in Different Treatments

Changes in C/N ratio under the three N management approaches will affect decomposition processes of straw after it is returned to the soil (Vigil and Kissel, 1991). The average straw C/N ratio of wheat or maize in conventional farming practice was lower than in the improved N_{min} or N balance treatments (Table 5) and the difference was significant ($P < 0.05$) in winter wheat but not in summer maize, and the ratio was lower in all N application treatments ($P < 0.05$) than in the controls (N_0 and N_0+C). In most cases neither straw return nor organic amendments had any significant effect on straw C/N ratio under the different N management practices. Average straw C/N ratio showed some year-to-year variation across both crops and in 2007 maize and 2008 wheat was significantly higher ($P < 0.05$) than in the other 2 yr because of the high grain and straw yields (Table S1) without substantial increase in N uptake (Table 4).

Soil Nitrate-Nitrogen Accumulation at 0- to 1- and 1- to 2-m Depths down the Soil Profile

The average NO_3–N accumulation in the rooting zone (0–1-m depth) of both crops in the treatments representing conventional farming practice was much higher than in the improved N_{min} or N balance method treatments (Table 6) and was higher in maize than in wheat, possibly because of greater N

Table 5. Straw C/N ratios after each harvest from 2007 to 2009.

Code†	Wheat (*n* = 3)			Maize (*n* = 3)			N management (*n* = 18)	
	2007	2008	2009	2007	2008	2009	Wheat	Maize
N_0	75.0 ± 0.04‡ab§	111.0 ± 7.94a	71.7 ± 3.05a	50.4 ± 0.03ab	42.4 ± 1.98bc	54.4 ± 0.15a	86.7 ± 4.87a	51.6 ± 1.72a
N_0+C	81.4 ± 7.79a	113.7 ± 2.07a	67.1 ± 4.24ab	54.4 ± 1.16a	59.5 ± 4.79a	48.3 ± 4.43a		
N_{con}	49.6 ± 5.83c	59.3 ± 0.37bc	45.7 ± 0.44c	42.6 ± 1.41c	31.0 ± 1.65c	32.0 ± 0.99b	49.6 ± 1.66c	37.2 ± 1.42b
N_{con}+C	48.4 ± 4.36c	49.0 ± 1.58c	45.9 ± 1.37c	39.2 ± 1.75c	45.0 ± 2.29b	33.6 ± 1.25b		
N_{min}	60.9 ± 4.92abc	65.3 ± 8.69bc	52.0 ± 2.73bc	45.3 ± 1.54bc	36.6 ± 5.15bc	33.5 ± 2.34b	63.4 ± 2.73b	40.8 ± 2.15b
N_{min}+C	71.3 ± 7.44ab	71.3 ± 2.35b	59.4 ± 2.49b	54.6 ± 4.90a	37.9 ± 1.92bc	36.7 ± 1.29b		
M_{bal}+C	56.4 ± 7.75bc	75.3 ± 10.1b	54.0 ± 2.39bc	43.4 ± 0.83bc	33.6 ± 3.54bc	35.2 ± 1.95b	63.9 ± 3.33b	39.6 ± 1.70b
W_{bal}+C	59.4 ± 4.70bc	79.8 ± 3.36b	58.4 ± 1.57b	45.8 ± 0.83bc	44.3 ± 6.03bc	35.5 ± 0.60b		
Avg.¶ (*n* = 18)	57.7 ± 3.04b	66.7 ± 3.38a	52.6 ± 1.51b	45.2 ± 1.47a	38.1 ± 1.97b	34.4 ± 0.72b		

† N_0, N_{min}, N_{con}, M_{bal}, and W_{bal} represent control, improved N_{min} test, conventional farming practice, cattle manure with nitrogen balance method, waste compost with nitrogen balance method; C represents straw return.

‡ Number represents mean ± standard error.

§ Means with the same lowercase letter are not significantly different in the same year (columns) among eight treatments; in the same crop (columns) among 4 N management regimes; and in the same crop ("Avg." row) among 3 yr ($P < 0.05$).

¶ Mean of above six N application treatments, not including N_0 and N_0+C treatments.

Table 6. Soil NO_3–N (kg N ha^{-1}) accumulation in 0- to 1-m soil profile after each harvest from 2007 to 2009.

Code†	Wheat (*n* = 3)			Maize (*n* = 3)			N management (*n* = 18)	
	2007	2008	2009	2007	2008	2009	Wheat	Maize
N_0	100.8 ± 53.6‡b§	9.7 ± 1.3b	8.7 ± 0.8b	51.1 ± 23.3d	7.1 ± 0.9d	30.1 ± 10.2d	35.6 ± 13.2b	28.0 ± 6.2d
N_0+C	75.8 ± 22.6b	7.3 ± 2.0b	11.1 ± 3.6b	41.3 ± 14.0d	9.9 ± 2.2d	28.2 ± 6.8d		
N_{con}	331.3 ± 99.3a	276.8 ± 41.8a	171.5 ± 46.8a	340.7 ± 29.6ab	233.3 ± 24.4ab	574.2 ± 31.2a	256.6 ± 27.2a	391.8 ± 33.2a
N_{con}+C	228.6 ± 38.2ab	328.9 ± 51.2a	202.7 ± 36.0a	455.3 ± 55.2a	252.9 ± 5.0a	494.4 ± 43.9a		
N_{min}	148.3 ± 17.8b	64.4 ± 4.1b	29.9 ± 11.9b	152.4 ± 35.5cd	49.0 ± 14.4d	165.5 ± 21.2c	62.0 ± 12.3b	111.6 ± 13.6c
N_{min}+C	78.6 ± 30.9b	29.7 ± 12.7b	21.2 ± 1.8b	92.5 ± 11.6d	58.8 ± 27.3cd	151.6 ± 12.7c		
M_{bal}+C	99.1 ± 31.3b	37.1 ± 5.4b	26.4 ± 2.2b	236.6 ± 21.6bc	180.6 ± 14.7b	279.0 ± 2.6b	51.4 ± 9.9b	201.2 ± 20.2b
W_{bal}+C	87.5 ± 24.4b	30.3 ± 7.7b	28.2 ± 7.1b	147.0 ± 49.4cd	107.1 ± 14.7c	257.1 ± 62.8bc		
Avg.¶ (*n* = 18)	162.3 ± 29.2a	127.9 ± 31.6ab	80.0 ± 20.6b	237.4 ± 33.2ab	147.0 ± 20.3b	320.3 ± 40.3a		

† N_0, N_{min}, N_{con}, M_{bal}, and W_{bal} represent control, improved N_{min} test, conventional farming practice, cattle manure with nitrogen balance method, waste compost with nitrogen balance method; C represents straw return.

‡ Number represents mean ± standard error.

§ Means with the same lowercase letter are not significantly different in the same year (columns) among eight treatments; in the same crop (columns) among 4 N management regimes; and in the same crop ("Avg." row) among 3 yr ($P < 0.05$).

¶ Mean of above six N application treatments, not including N_0 and N_0+C treatments.

mineralization in the hot and wet summer maize seasons. There were no differences among controls, improved N_{min} and N balance treatments in the winter wheat seasons, indicating that the latter two methods worked well in producing low residual NO_3–N after harvest. In contrast, the two organic treatments (M_{bal}+C, W_{bal}+C) led to significantly higher residual NO_3–N in summer maize compared with the improved N_{min} treatments, which suggests there is potential for further reduction in fertilizer N rate. Straw return did not change soil NO_3–N accumulation at the 0- to 1-m depth due to the complexity of N mineralization and immobilization processes in the soil, different N application rates (e.g., N_{min} vs. N_{min}+C in Table 2), residual NO_3–N in the previous crop and large spatial variation in NO_3–N among replicate plots. Average soil NO_3–N accumulation at the 0- to 1-m depth showed high variation across years for both crops, a result of the combination of N application rate, soil N mineralization, crop N uptake, and leaching. For example, the extremely high NO_3–N accumulation after the 2009 maize harvest may be explained by low crop N uptake (due to lodging) and less leaching (due to lower precipitation).

Similarly, the average accumulation of NO_3–N at 1- to 2-m depth under the conventional farming practice (N_{con} and N_{con}+C) was higher than in the controls, improved N_{min} or N balance treatments, indicating a substantial risk of NO_3–N leaching in these treatments (Table 7). Moreover, NO_3–N was much higher following maize seasons than following wheat, perhaps due to higher N mineralization and NO_3–N leaching in the hot and wet maize seasons. There were no differences among control, improved N_{min} and N balance treatments in either crop, indicating that the latter two measures succeeded in controlling NO_3–N leaching. Straw return and organic amendments also produced no change in soil NO_3–N accumulation at 1- to 2-m depth; the explanation may be same as for 0- to 1-m soil depth as described above. Average soil NO_3–N accumulation at the 1- to 2-m depth showed significant variation across years in the maize seasons. The high value in the 2008 maize season may reflect higher NO_3–N leaching as a result of heavy summer rainfall.

The distribution of NO_3–N from 0 to 2 m in the soil profile after each crop harvest can explain the trends of NO_3–N movement and thus further illustrate NO_3–N leaching in

Table 7. Soil NO_3–N (kg N ha^{-1}) accumulation at 1- to 2-m soil depth after each harvest from 2007 to 2009.

Code†	Wheat (*n* = 3)			Maize (*n* = 3)			N management (*n* = 18)	
	2007	2008	2009	2007	2008	2009	Wheat	Maize
N_0	80.6 ± 26.6‡a§	61.7 ± 21.0a	42.5 ± 19.2b	117.7 ± 26.7ab	54.0 ± 16.4b	66.5 ± 32.0c	68.3 ± 8.6b	96.5 ± 12.0b
N_0+C	78.8 ± 13.0a	71.5 ± 21.0a	74.9 ± 13.7b	123.1 ± 24.6ab	130.8 ± 4.7b	86.5 ± 29.1b		
N_{con}	78.9 ± 23.2a	125.9 ± 26.5a	199.7 ± 27.5a	182.1 ± 22.6a	352.2 ± 89.0a	295.8 ± 36.2a	115.3 ± 14.4a	249.2 ± 24.9a
N_{con}+C	60.7 ± 14.5a	116.9 ± 19.9a	110.1 ± 31.5b	160.0 ± 20.2ab	318.2 ± 22.7a	186.7 ± 18.1ab		
N_{min}	63.9 ± 16.5a	101.1 ± 24.4a	53.8 ± 8.9b	116.8 ± 3.1ab	147.5 ± 30.2b	150.5 ± 26.7b	73.0 ± 8.2b	136.2 ± 13.0b
N_{min}+C	81.9 ± 25.4a	75.3 ± 16.9a	62.4 ± 6.8b	128.2 ± 19.2ab	146.9 ± 60.7b	127.0 ± 5.5b		
M_{bal}+C	67.9 ± 28.4a	82.9 ± 29.3a	93.8 ± 25.6b	88.5 ± 8.2b	144.7 ± 37.5b	145.7 ± 47.7b	76.3 ± 10.4b	135.8 ± 16.3b
W_{bal}+C	85.8 ± 18.4a	77.9 ± 27.3a	49.5 ± 9.7b	104.3 ± 27.0b	196.6 ± 46.5ab	134.9 ± 23.3b		
Average¶ (*n* = 18)	73.2 ± 9.1a	96.7 ± 11.0a	94.9 ± 14.9a	130.0 ± 10.7b	217.7 ± 29.5a	173.5 ± 18.2ab		

† N_0, N_{min}, N_{con}, M_{bal}, and W_{bal} represent control, improved N_{min} test, conventional farming practice, cattle manure with nitrogen balance method, waste compost with nitrogen balance method; C represents straw return.

‡ Number represents mean ± standard error.

§ Means with the same lowercase letter are not significantly different in the same year (columns) among eight treatments; in the same crop (columns) among 4 N management regimes; and in the same crop ("Avg." row)) among 3 yr ($P < 0.05$).

¶ Mean of above six N application treatments, not including N_0 and N_0+C treatments.

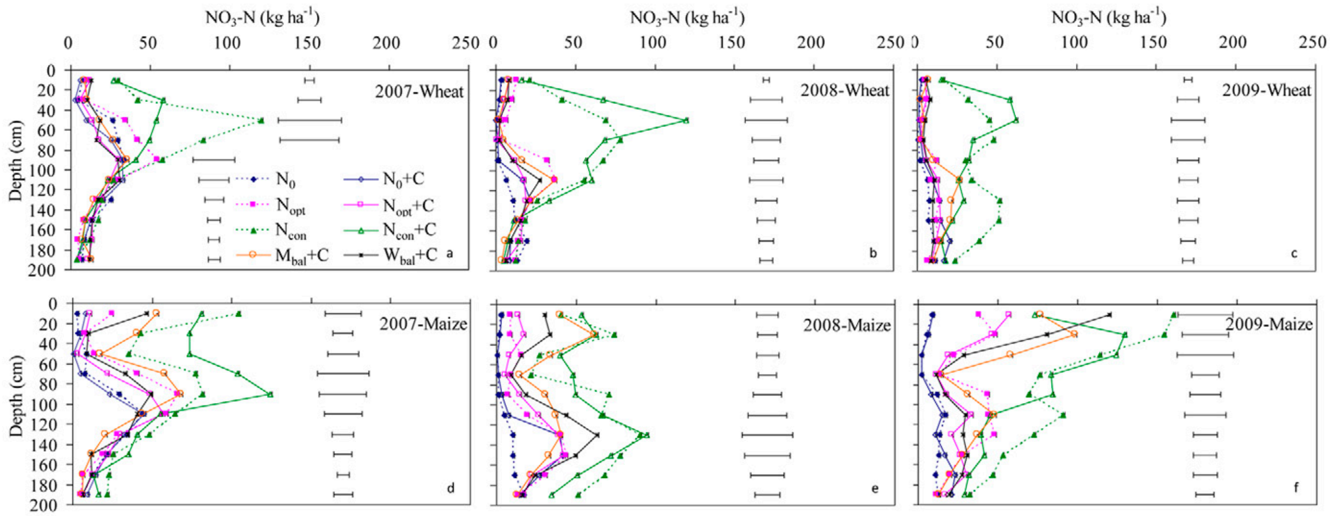

Fig. 3. Soil NO_3–N (kg N ha^{-1}) distribution at 0 to 2 m in the soil profile after each harvest from 2007 to 2009. Horizontal line denotes the LSD 0.05 value.

different cropping seasons and different treatments (Fig. 3). In 2007 and 2008 the peak of NO_3–N in the summer maize seasons (Fig. 3 d, 3e) moved deeper in the soil profile compared to the winter wheat seasons (Fig. 3a,3b) because there was much more precipitation during the growth of summer maize, especially in 2008 (Fig. 2a). In 2009 there was less summer precipitation than in the previous 2 yr and the peak of NO_3–N in summer maize was within the top 1 m of the soil profile (Fig. 3f). Two peaks of residual NO_3–N in the winter wheat season in 2009 (Fig. 3c) appeared between 0 and 2 m and this may have been related to a lack of synchrony between crop N demand and N application rate.

Nitrate to a depth of 2 m was always higher in the conventional treatments (N_{con} and N_{con}+C) than in the other three N management approaches (N_0, N_0+C; N_{min}, N_{min}+C; and M_{bal}+C, W_{bal}+C). In particular, after the 2008 maize, 2009 wheat, and 2009 maize harvests NO_3–N to a depth of 2 m indicated high NO_3–N leaching potential in these three seasons according to the rainfall pattern. Nitrate to 2-m depth in the organic amendment (M_{bal}+C and W_{bal}+C) treatments was higher following maize than following wheat because the fertilizer N rate in the former was higher than in the latter based on the balance method, taking into account the 20% availability of total N in the organic manure and compost in the maize season (Table 2). In view of the high NO_3–N leaching potential in these manure treatments with high soil or manure N mineralization in the hot and wet maize seasons, it might be possible to further modify the parameters of the balance method and increase the percentage availability of the total N in organic manures to 40% and reduce the target residual NO_3–N at 0- to 100-cm depth (i.e., the rooting zone) from 100 to 80 kg N ha^{-1} for environmental protection, in accordance with data shown in Table 6 and the results reported by Cui et al. (2008d).

Nitrogen Balance in Different Treatments

The negative values in Table 8 may be explained as NO_3–N accumulation at 0- to 1-m depth in the soil profile. In the control treatments the apparent N mineralization capacity of this soil did not appear to decrease during the successive six cropping seasons (Table 8), indicating a high potential N supply capacity of the soil, and can also be partly explained by high total N deposition from the atmosphere (the average reached 89 kg N ha^{-1} per year; see Ju et al., 2009). The apparent N loss was the largest using conventional farming practices (N_{con} and N_{con}+C) and lowest using the improved N_{min} method (N_{min} and N_{min}+C) in the successive six cropping seasons. Very large losses occurred in all N

Table 8. Nitrogen balances (kg N ha^{-1}) in different treatments after each harvest from 2007 to 2009.

Code†	Wheat			Maize		
	2007	2008	2009	2007	2008	2009
N_0‡	70.6	82.3	70.9	73.4	114.7	111.1
N_0+C‡	45.1	98.4	66.5	103.6	86.1	110.4
N_{con}§	12.0	249.8	231.8	140.7	203.6	−191.3
N_{con}+C§	74.9	305.9	189.1	−68.5	235.3	−96.1
N_{min} §	−0.7	111.3	27.3	−43.8	49.7	−50.2
N_{min}+C§	85.5	153.8	34.6	30.5	0.5	−44.1
M_{bal}+C§	31.5	225.8	131.4	−60.9	−59.6	−68.7
W_{bal}+C§	50.6	170.4	138.7	49.7	31.5	−47.9

† N_0, N_{min}, N_{con}, M_{bal}, and W_{bal} represent control, improved N_{min} test, conventional farming practice, cattle manure with nitrogen balance method, waste compost with nitrogen balance method; C represents straw return.

‡ Apparent N mineralization = N_{uptake} + NO_3–N_{post}- NO_3–$N_{previous}$.

§ Apparent N loss = apparent N mineralization + $N_{fertilizer}$ + NO_3–$N_{previous}$- N_{uptake}- NO_3–N_{post} where N_{uptake} is N uptake by crop aboveground at crop harvested (Table 4), NO_3–N_{post} is residual NO_3–N in 0- to 100-cm soil depth after crop harvested, and NO_3–$N_{previous}$ is residual NO_3–N in 0- to 100-cm soil depth after the previous crop harvest (Table 6), NO_3–N concentration in 0 to 1 m root zone after summer maize harvest in October 2006 was 171.8 ± 10.3 kg N ha^{-1}. The apparent N loss in straw removal treatments used the value of apparent N mineralization in N_0 treatment, correspondingly, straw return treatments used the value in N_0+C treatment; the negative values may be explained by accumulation of NO_3–N; the calculated available N amount from organic fertilizer in each crop was also taken into account in the N fertilizer application (National Extension Center of Agriculture Technique in China, 1999).

treatments in the 2008 wheat season due to substantial leaching of NO_3–N from the top 1 m of the soil profile by heavy rainfall and very high NO_3–N accumulation occurred in the 2009 maize season due to low N uptake and lower NO_3–N leaching from the top 1m of the soil profile by low rainfall.

DISCUSSION

Potential Fertilizer Nitrogen Saving

Our results show that 45 to 61% of fertilizer N may be saved without reducing crop yield over the initial 3 yr and with a significant reduction in NO_3–N accumulation in the top 2 m of the soil profile using the improved N_{min} method. Even more fertilizer N (93 and 77%) could be saved in manure treatments during wheat growth using the N balance approach and taking manure N availability into account. A large number of field experiments on intensive double-cropping systems (winter wheat/summer maize on the North China Plain and rice (*Oryza sativa* L.)/wheat in Taihu region, south China) have also shown 30 to 60% saving of fertilizer N without applied manure (Ju et al., 2009). Other published studies on wheat/maize systems in northern China have consistently demonstrated opportunities for considerable fertilizer savings of 61% in winter wheat (Cui et al., 2008d) and 40% in summer maize (Cui et al., 2008b). The reasons why farmers use such an excess of fertilizer N have been explained by Ju et al. (2009). These include an extra quantity of N applied as an "insurance" dressing against yield loss in years with poorer crop performance, low retail prices for fertilizer N because of government subsidy, and high earnings from off-farm activities by farmers. Moreover, farmers in this region usually apply fertilizer N with no consideration of the N supplied by manures, leading to overfertilization and degradation of the environment (He et al., 2007). The N_{min}+C received more chemical N during the first 3 yr compared with the N_{min} treatment because fertilizer N was immobilized by the high C/N ratio wheat or maize straw (Tomar and Reiger, 1981; Christopher and Lal, 2007). The immobilized N would potentially be available for mineralization in subsequent years and straw return would be expected to increase the soil organic N pool with lower fertilizer N inputs over the long term. The present study has also shown that failure to take the N supplying capacity of organic manures into account can lead to excessive N application. Saving fertilizer N for environmental protection and reducing farming costs is still a major challenge for the local extension services if these improved N management practices are adopted by farmers.

Re-evaluation of Parameters for Calculating Nitrogen Rate in Two Nitrogen Management Approaches

The improved N_{min} method and balance method work well in winter wheat for optimum crop yield and control of NO_3–N leaching using existing parameters for calculating the fertilizer N application. In the improved N_{min} test method, soil N mineralization can be offset by synchronizing crop N uptake and N supply with double or triple soil N_{min} tests in a season (Tables 6 and 7) according to the improved N_{min} method (Chen et al., 2006). However, excessive accumulation of NO_3–N at 0- to 1- and 1- to 2-m depth in the soil profile occurs during the growth of summer maize, especially in manure treatments using the balance method (Tables 6 and 7). To further reduce environmental risks, the target residual NO_3–N in the top 1-m rooting zone in summer maize may be adjusted to 80 kg N ha^{-1} in both the improved N_{min} and balance methods, and the percentage of total N that is available in organic manures may also need to be adjusted to 40% for the maize component of the cropping sequence when manure is applied. These parameters in the maize season would have further decreased NO_3–N loss by 61.7 and 55.3 kg ha^{-1} in M_{bal}+C and W_{bal}+C treatments based on the mean calculated N amounts from 2007 to 2009. Cui et al. (2008a) used data from a large number of field experiments and concluded that 87 to 180 kg ha^{-1} soil residual NO_3–N in the top 90 cm after harvest is a safe target range for maintaining high maize yields and low leaching risk. Thus, values of 40% available manure N and 80 kg N ha^{-1} target residual NO_3–N in the summer maize season would be suitable for the relatively light texture of the agriculture soils on the North China Plain under the prevailing high temperatures and humidity.

The consistently high potential N supplying capacity of the soil in control treatments over time can be explained by high soil N mineralization rates and high total N deposition from the atmosphere (Ju et al., 2009). During summer maize growth in this region, Cui et al. (2008b) also found an average of 127 kg N ha^{-1} from soil N mineralization and environmental N deposition. Root N might also be an impact factor when the N balance is calculated in each harvested crop. Lupwayi et al. (2006) reported that N release from wheat roots was about 2 kg N ha^{-1} in the first year of decomposition and N was likely to be released in the subsequent years also. However, in the long run, root N participates in soil N cycling and becomes soil indigenous N. Thus, it can be accepted that the calculated N balance is based on apparent N mineralization and loss without considering the effect of root N. In future work all these N factors must be taken fully into account and more work is needed to validate the calculated N balance.

Due to practical difficulties and the lack of satisfactory methods for the direct measurement of NO_3–N leaching in situ in this semiarid area (Mack et al., 2005), we determined NO_3–N concentrations at 1- to 2-m depth in the soil profile to illustrate NO_3–N leaching in the current study. However, direct observation of NO_3–N leaching is important for evaluation of the environmental impacts of different N management approaches. Future studies will attempt to measure NO_3–N leaching below 1-m soil depth directly using soil suction cups with drainage calculation by modeling (Mack et al., 2005), together with evaluation of other N cycle processes such as NH_3 volatilization and greenhouse gas emissions.

Nitrogen fertilizer use efficiency can be further increased and N losses further reduced by employing improved crop management including plant density adjustment to prevent lodging in maize and use of accurate weather forecast information for efficient water management to avoid excessive NO_3–N leaching (Ju et al., 2009).

Decreasing Straw Carbon/Nitrogen Ratio in Conventional Farming Practice

Narrow straw C/N ratios caused by excessive fertilizer N application can cause plants to become more susceptible to insect attack, fungal diseases, and lodging. In addition, the lower C/N ratios (Christopher and Lal, 2007) and high initial N concentrations (Bosatta and Staaf, 1982) of straw are associated with more rapid decomposition rates (Vigil and Kissel, 1991), and net N mineralization may occur when the N concentration of straw exceeds 0.54% (Williams et al., 1968). Furthermore, high available N in the soil may stimulate straw N mineralization and increase CO_2 and N_2O emission with straw-returned decomposition (Jensen, 1994; Toma and Hatano, 2007), thereby reducing N immobilization (Sain and Broadbent, 1977) and making the buildup of soil organic N and C pools difficult (Eagle et al., 2000). On the other hand, narrow straw C/N ratios can increase the N availability for the crop (Vigil and Kissel, 1991) and reduce the risk of yield decrease by straw-induced N immobilization. It is complex combining improved soil fertility (C and N) and straw N bioavailability in response to changes in straw C/N ratio. Generally, soil N supply, yield, and N uptake will increase after long-term straw application (Eagle et al., 2000), therefore it is necessary to examine the effects of high straw N concentration with excessive chemical fertilizer N application on C and N cycling and distribution in the soil-crop system and the quantity of organic N source in place of chemical fertilizer N in future studies.

CONCLUSIONS

Comparing conventional farming practice in cropping in each season, the improved N_{min} method with two soil N_{min} tests and the N balance method can save chemical fertilizer N application without reducing crop yield. The improved N_{min} method decreases NO_3–N accumulation at 0 to 1 m and nitrate leaching to 1 to 2 m in the soil profile in the winter wheat/summer maize double cropping system but the parameters in the N balance method only work well in the winter wheat season and further adjustment is needed in the summer maize season because the soil has strong soil N (or manure N) mineralization and high nitrate leaching potential in the hot, wet summers on the North China Plain. The parameters of the N balance method in the summer maize season might be adjusted to 80 kg N ha^{-1} target residual NO_3–N in the 0- to 1-m root zone and 40% availability of total N in organic manure in future studies. In addition, the narrow straw C/N ratio with excessive fertilizer N application in conventional farming practices can lead to the double effect of straw N availability increasing and soil N immobilization decreasing, with corresponding changes and stabilities of different C and N pools. Greenhouse gas emissions in conventional farming practices should also be further evaluated over the long term.

SUPPORTING INFORMATION AVAILABLE

Additional information on straw yields, grain protein contents, and grain C/N ratios can be found in the online version at doi: http://www.cau.edu.cn/zihuan/ms.php?ID=68.

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