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Soil nitrate accumulation and leaching in conventional, optimized and organic cropping systems

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ABSTRACT

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Excessive nitrogen (N) and water input, which are threatening the sustainability of conventional agriculture in the North China Plain (NCP), can lead to serious leaching of nitrate-N (NO_3^--N). This study evaluates grain yield, N and water consumption, NO_3^--N accumulation and leaching in conventional and two optimized winter wheat-summer maize double-cropping systems and an organic alfalfa-winter wheat cropping system. The results showed that compared to the conventional cropping system, the optimized systems could reduce N, water consumption and NO_3^--N leaching by 33, 35 and 67–74%, respectively, while producing nearly identical grain yields. In optimized systems, soil NO_3^--N accumulation within the root zone was about 80 kg N/ha most of the time. In the organic system, N input, water consumption and NO_3^--N leaching was reduced even more (by 71, 43 and 92%, respectively, compared to the conventional system). However, grain yield also declined by 46%. In the organic system, NO_3^--N accumulation within the root zone was generally less than 30 kg N/ha. The optimized systems showed a considerable potential to reduce N and water consumption and NO_3^--N leaching while maintaining high grain yields, and thus should be considered for sustainable agricultural development in the NCP.

Keywords: sustainable agriculture; crop rotation; optimized management; environmental consequence; macronutrient

The North China Plain (NCP) is an important, intensive grain production region of China. The winter wheat-summer maize double cropping system is the primary planting pattern in this area. On the NCP, the overuse of nitrogen (N) fertilizers combined with excessive irrigation, or heavy summer rainfall, results in significant NO_3^--N leaching (Fang et al. 2006, Wang et al. 2010). The challenge of reducing NO_3^--N accumulation in soil and subsequent leaching while guaranteeing high grain yield has become a key regional topic, attracting attention from numerous agronomists, environmentalists and agricultural policymakers (Ju et al. 2009, Chen et al. 2011).

Many studies have shown that strict control of the amount of N fertilization, coupled with effective application methods, is the key to en-

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sure the high target yield, while reducing the soil NO_3^--N accumulation and leaching (Ercoli et al. 2013). NO_3^--N leaching could be further reduced by optimized irrigation management (Gheysari et al. 2009). Furthermore, the optimizations of other comprehensive agronomic measures, such as tillage and straw managements, are important options to improve the N utilization by crops and to reduce the soil NO_3^--N accumulation and leaching (Beaudoin et al. 2005). Most recent studies that address soil NO_3^--N leaching in the NCP focus on only one or two factors (Fang et al. 2006, Wang et al. 2010). Research studies that investigate multiple factors and their relative impacts are few. It is suggested that current conventional intensive agriculture can be improved by an integrated approach, which includes optimization of N fertilization, irrigation regime, tillage method and straw management to maintain high requisite yields while reducing N fertilizer, irrigation water and minimizing NO_3^--N leaching and subsequent groundwater contamination.

Organic agriculture processes generally require lower resource input, e.g. reduced dependence on synthetic chemicals, yielding more favourable environmental effects, although the overall costs of organic vs. conventional agricultural operations remain a subject of substantial debate (Mäder et al. 2002, Kramer et al. 2006). Conversion to organic agricultural practices is likely to have profound impacts on N transformation, plant uptake and accumulation, and leaching. While continuation of these organic practices may improve grain yield and have long-term positive environmental consequences, few studies were conducted on NO_3^--N leaching within organic cropping systems in the NCP.

It was hypothesized that an organic cropping system would reduce NO_3^--N leaching relative to a conventional cropping system due to lower N and water inputs. It was further hypothesized that the optimized cropping system will maintain or even increase grain yield, while reducing NO_3^--N leaching as a consequence of the integration of optimized N fertilization, irrigation, tillage, straw and other agronomic management techniques. The objectives of this study were to evaluate performance of one conventional cropping system, two optimized cropping systems and one organic cropping system in terms of soil NO_3^--N accumulation, soil NO_3^--N leaching and grain yields over a two-year period, and to further determine which cropping system best decreases NO_3^--N leaching while maintaining or increasing grain yield.

MATERIAL AND METHODS

The field experiment was conducted from 2008 to 2010 at the Huantai Experimental Station (36°57.75'N, 117°59.21'E), China Agricultural University, located in the Huantai County, Shandong province. This area has a typical temperate monsoon climate. The annual mean temperature is 12.5°C and the annual mean precipitation is 550 mm (range 235–1078 mm). Daily mean air temperature and daily precipitation at the experimental site from 2008 to 2010 are shown in Figure 1. The soil of the experimental field originates from alluvial sediments of the Yellow River and is classified as Aquic Inceptisol. The physicochemical properties of the experiment site are reported in Table 1.

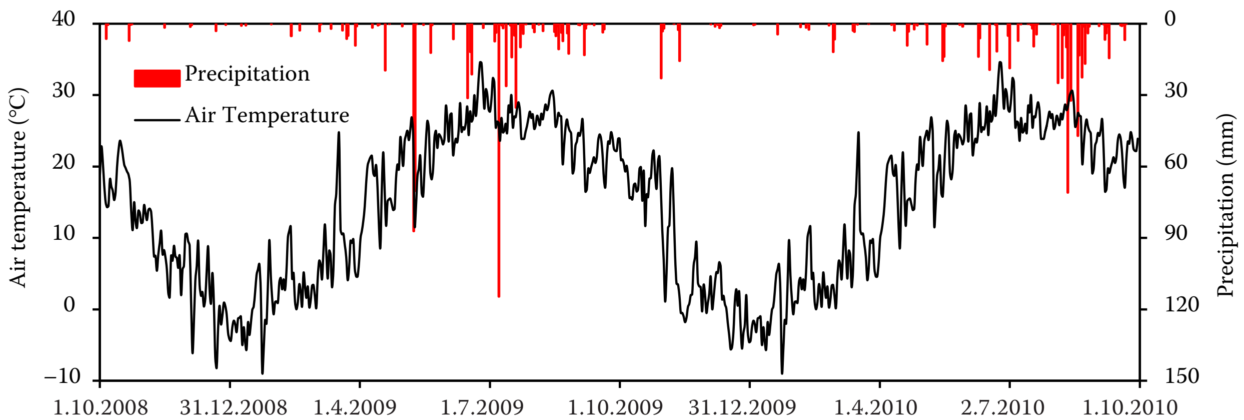

Figure 1. Daily mean air temperature and daily precipitation at the experimental site

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Table 1. Soil physicochemical characteristics in the experimental site

Soil depth (cm)	pH_{H_2O}	Organic C	Total N	Olsen-P	Available K	Bulk density (g/cm^3)	Field water capacity (cm^3/cm^3)	Sand	Silt	Clay
		(g/kg)		(mg/kg)					(%)	
0–20	7.71	10.88	0.92	9.97	110.50	1.52	0.27	36.0	52.6	11.4
20–40	7.88	4.83	0.67	2.24	93.75	1.53	0.26	31.4	47.8	20.8
40–110	7.52	3.24	0.35	1.18	105.17	1.45	0.25	10.6	56.8	32.6
110–170	7.51	1.60	0.22	1.03	70.89	1.53	–	19.8	47.6	32.6
170–200	7.63	1.32	0.20	0.77	59.50	1.59	–	18.9	46.4	34.7

A completely randomized block design with four treatments and four replications was used. Each plot was 450 m^2 (18 × 25). The control was a conventional winter wheat-summer maize double-cropping system following current local farming practices (CON). The other three cropping systems in the study were: (i) optimized winter wheat-summer maize double-cropping system with balanced N fertilization (manure and urea) and optimal water management (OMW); (ii) optimized winter wheat-summer maize double-cropping system with balanced N fertilization (urea only) and optimal water management (OFW), and (iii) an organic alfalfa-winter wheat cropping system with low N and water input management (ORG). Three local common cultivars (winter wheat Jimai 22, summer maize Zhengdan 958 and alfalfa Jinhuanghou) were selected in this experiment.

For CON, the local conventional irrigation practice was fully adopted. Adjusted for rainfall, the irrigation frequency was set at three to five times for winter wheat and one or two times for summer maize. In OMW, OFW and ORG, optimized irrigation was conducted in the winter wheat seasons by testing soil water content before the critical crop growth stages (winter wheat seasons: before sowing, at stages of seedling establishment, jointing and flowering; summer maize seasons: before sowing, at stages of trefoil, tenth leaf and silking). The soil water content target was between 45% and 80% of the plant available water content, which was determined by measuring field water capacity and the corresponding wilting point (Zhao et al. 2006). Irrigation water was delivered by 15 cm plastic hoses. The quantity of irrigation water was determined using flow meters. In CON, the N application rate followed local farming practices, which was 300 kg N/ha (urea) applied during each crop season. For OMW and OFW, N application rates were calculated for a balanced N fertilization method:

$$N_{fertilization} = N_{uptake} + N_{residue} - N_{soil} \quad (1)$$

Where: $N_{fertilization}$ – N application rate (kg N/ha); N_{uptake} – N uptake by the crop (180 kg N/ha); $N_{residue}$ – accumulated NO_3^--N in the root zone (0–100 cm) after harvest (80 kg N/ha); N_{soil} – accumulated NO_3^--N in the root zone before sowing.

In OMW, manure (1/3 total N) and urea (1/6 total N) were applied as basal fertilizers and urea (1/2 total N) was applied once as topdressing. For CON and OFW, N (urea) was applied separately at two different times and the basal fertilizer:topdressing ratio was 1:1. Basal fertilizer was applied with sowing. Topdressing was applied at winter wheat jointing stage and summer maize tenth leaf stage. In these three systems (CON, OMW and OFW), triple superphosphate was applied at a rate of 52.4 kg P/ha during the winter wheat growing seasons. Potassium sulfate and zinc sulfate were applied during the summer maize growing seasons at rates of 83.0 kg K/ha and 6.1 kg Zn/ha, respectively. In ORG, all N was supplied by manure, applied once as the basal fertilizer. More detailed field management practices in the four systems are summarized in Table 2.

Three borings were collected in each plot with a 3-cm diameter gouge auger and samples from the same depth intervals were mixed and sieved (2 mm). NO_3^--N from the soil samples was extracted with a 0.01 mol/L $CaCl_2$ solution (Chen et al. 2006) and NO_3^--N in the extracted liquid was determined with a flow analyser (TRAACS 2000, Norderstedt, Germany). It was noticed that since the NO_3^--N monitor was employed within the 0–200 cm soil profile, seasonal NO_3^--N leaching was approximately equal to the value of residual NO_3^--N in the 100–200 cm layer after harvest, minus the amount available before sowing, as follows (Liu et al. 2003):

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Table 2. Detailed field management practices in the four different cropping systems

Crop season	Management practices	CON	OMW	OFW	ORG
2008/10–2009/06	crop	wheat	wheat	wheat	alfalfa
	N input (kg N/ha)	300	231	231	74[a]
	irrigation (mm)	325	250	250	250
	tillage before crop sowing	rotary tillage	deep ploughing	no-tillage	rotary tillage
	seeding rate (kg/ha)	150	120	120	18
	straw management	return	return	return	—[b]
2009/06–2009/09	crop	maize	maize	maize	alfalfa
	N input (kg N/ha)	300	180	175	—
	irrigation (mm)	75	75	75	—
	tillage before crop sowing	no-tillage	rotary tillage	no-tillage	—
	plant density (plants/ha)	50 000	65 000	65 000	—
	straw management	burn	return	return	return[c]
2009/10–2010/06	crop	wheat	wheat	wheat	wheat
	N input (kg N/ha)	300	204	208	197
	irrigation (mm)	450	275	275	275
	tillage before crop sowing	rotary tillage	deep ploughing	no-tillage	rotary tillage
	seeding rate (kg/ha)	150	120	120	120
	straw management	return	return	return	return
2010/06–2010/09	crop	maize	maize	maize	alfalfa
	N input (kg N/ha)	300	189	189	74
	irrigation (mm)	75	—	—	—
	tillage before crop sowing	no-tillage	rotary tillage	no-tillage	rotary tillage
	plant density (plants/ha)	50 000	65 000	65 000	2 100 000
	straw management	burn	return	return	—
Total over 2 years	total N input (kg N/ha)	1200	804	803	345
	irrigation rate (mm)	925	600	600	525

[a]Cattle manure: organic C 23.56%; total N 1.41%, C:N ratio 16.71:1; [b]Represents no data in this season; [c]Represents crop residue retention. CON – control; OMW – optimized winter wheat-summer maize double-cropping system with balanced N fertilization (manure and urea) and optimal water management; OFW – optimized winter wheat-summer maize double-cropping system with balanced N fertilization (urea only) and optimal water management; ORG – an organic alfalfa-winter wheat cropping system with low N and water input management

$$NO_3^-\text{-N leached} = NO_3^-\text{-N}_{\text{residual 100–200 cm after harvest}} - NO_3^-\text{-N}_{\text{residual 100–200 cm before sowing}} \quad (2)$$

The food equivalent unit (FEU) was chosen as the equivalent reference of grain yield (Ren and Lin 2006). The equivalent grain yield can be expressed as:

$$\text{Grain yield} = \text{yield} \times \text{FEU} \quad (3)$$

The yields of wheat and maize are expressed by dry matter weight of grain, while the yield of alfalfa is expressed by dry matter weight of hay. The yield was adjusted to 13% moisture. The FEU values of wheat, maize and alfalfa are 0.991, 1.001 and 0.7, respectively. The grain yield in this paper was specifically indicated as the equivalent grain yield.

For the four cropping systems, grain yield and NO_3^--N leaching were analysed using one-way ANOVA in the SAS 8.1 software (SAS Institute Inc., Cary, USA). A mixed ANOVA model with four treatments and four seasons was used to assess the overall variability of grain yield and NO_3^--N leaching.

RESULTS

In a 2-year period, the grain yields ranged from 28 127 to 28 482 kg/ha under the three wheat-maize double cropping systems (CON, OMW, OFW) and there were no significant differences

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Table 3. Grain yields (kg/ha) in different cropping systems over a 2-year period

Crop season	CON	OMW	OFW	ORG
2008/10–2009/06	7180 ± 701[a]	7504 ± 359[a]	7465 ± 496[a]	5458 ± 760[b]
2009/06–2009/09	7250 ± 533[a]	7159 ± 368[a]	8062 ± 707[a]	3721 ± 682[b]
2009/10–2010/06	6685 ± 492[b]	7292 ± 304[a]	6948 ± 265[ab]	4026 ± 322[c]
2010/06–2010/09	7366 ± 789[a]	6172 ± 595[b]	5968 ± 491[b]	2196 ± 410[c]
Total	28 482 ± 2356[a]	28 127 ± 684[a]	28 444 ± 394[a]	15 401 ± 801[b]
Source of variation: treatment***; season***; treatment × season***				

Lowercase letters in the same row indicate a significant difference in different treatments (P < 0.05); ***P < 0.001. CON – control; OMW – optimized winter wheat-summer maize double-cropping system with balanced N fertilization (manure and urea) and optimal water management; OFW – optimized winter wheat-summer maize double-cropping system with balanced N fertilization (urea only) and optimal water management; ORG – an organic alfalfa-winter wheat cropping system with low N and water input management

among them (Table 3). The grain yield of ORG was only 15 401 kg/ha, which was significantly lower than the other three systems. Fertilization and irrigation optimization (OMW and OFW)

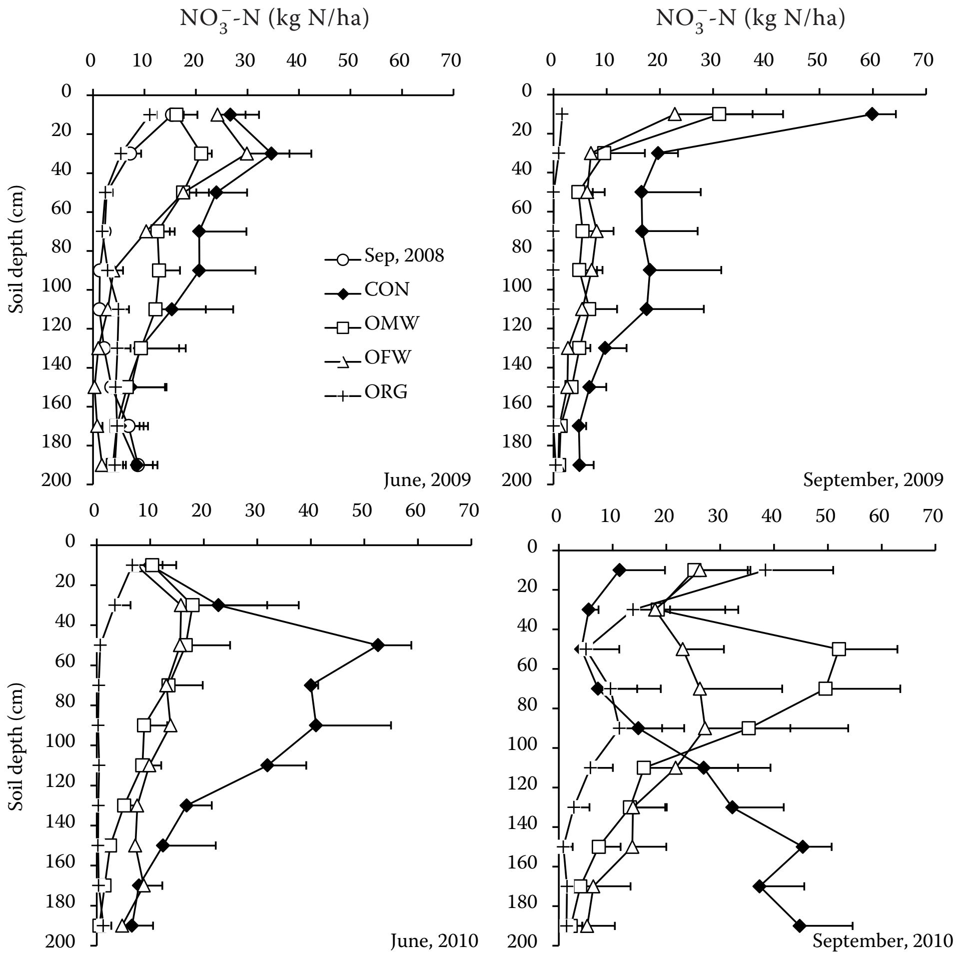

Figure 2. Distribution of NO_3^--N in the 0–200 cm soil profile after crop harvest in different cropping systems. Bars represent the standard error. CON – control; OMW – optimized winter wheat-summer maize double-cropping system with balanced N fertilization (manure and urea) and optimal water management; OFW – optimized winter wheat-summer maize double-cropping system with balanced N fertilization (urea only) and optimal water management; ORG – an organic alfalfa-winter wheat cropping system with low N and water input management

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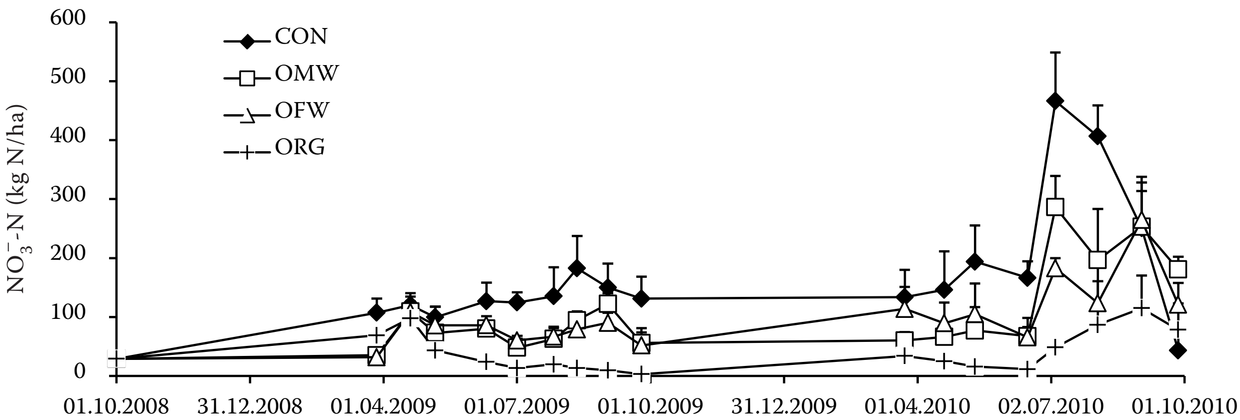

Figure 3. Dynamics of NO_3^--N accumulation in the 0–100 cm soil profile in different cropping systems. Bars represent the standard error. CON – control; OMW – optimized winter wheat-summer maize double-cropping system with balanced N fertilization (manure and urea) and optimal water management; OFW – optimized winter wheat-summer maize double-cropping system with balanced N fertilization (urea only) and optimal water management; ORG – an organic alfalfa-winter wheat cropping system with low N and water input management

reduced N and water input by 33% and 35%, respectively, compared to CON (Table 2). For ORG, N and water inputs were reduced by 71% and 43%, respectively, but the grain yield was significantly lower (by 46%) than CON.

It was found that after the crop harvest in June 2009 and September 2009, in the CON, OMW and OFW treatments NO_3^--N mainly accumulated in the upper 100 cm of soil (Figure 2). After the crop harvest in June 2010, NO_3^--N still accumulated primarily within the 0–100 cm profile, but did show a tendency to migrate to deeper soil layers in CON. In the OMW, OFW and ORG treatments, few changes in N distribution were noted when compared to the previous growing season. After the crop harvest in September 2010, NO_3^--N had accumulated substantially at a soil depth of 100–200 cm in CON, with peak NO_3^--N concentrations at the deepest layers (150 cm and 200 cm). In OMW, OFW and ORG, NO_3^--N still mainly accumulated in the upper 100 cm of soil.

The NO_3^--N dynamics were profoundly influenced by different cropping systems (Figure 3). In CON, during the whole rotation cycle, most soil NO_3^--N accumulations within the root zone were about 150 kg N/ha, with a maximum up to 466 kg N/ha. When continuous heavy rain occurred in August 2010, large quantities of accumulated NO_3^--N in topsoil quickly migrated to the deeper layers, triggering leaching. In OMW and OFW, the accumulation of NO_3^--N in the 0–100 cm soil layer was about 80 kg N/ha most of the time. In ORG, the NO_3^--N accumulation in soil was therefore kept relatively low; it was generally less than 30 kg N/ha in the root zone.

Over two years the total amount of leached NO_3^--N was 193.11 kg N/ha in CON (Table 4). In total, leached amounts were 50.74 kg N/ha and 63.36 kg N/ha, respectively. The two optimized cropping systems reduced NO_3^--N leaching by 74% and 67%, respectively, compared to the CON. The total leaching of NO_3^--N in ORG was just 15.23 kg N/ha. Compared to the CON, ORG could significantly reduce NO_3^--N leaching by 92%.

DISCUSSION

At present, the majority of agronomists believe that optimizing conventional intensive agriculture could lead to a reduction in resource consumption and the associated environmental pollution while maintaining high grain yield (Tilman et al. 2002, Galloway et al. 2008, Mueller et al. 2012). Studies conducted in the NCP have shown that N input reductions of 30–60% can be achieved through optimization of N management alone, without sacrificing grain yield (Ju et al. 2009). The results showed that the two optimized cropping systems reduced N fertilizer input, water consumption and NO_3^--N leaching by 33, 35 and 67–74%, respectively, compared to the conventional cropping system, while also generating nearly identical grain yields (Tables 2–4). In the optimized systems, soil NO_3^--N accumulation within the root zone was

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Table 4. NO_3^--N leaching (kg N/ha) in different cropping systems

Crop season	CON	OMW	OFW	ORG
2008/10–2009/06	22.97 ± 34.34[a]	13.94 ± 30.25[a]	–15.81 ± 2.45[b]	0.44 ± 8.98[ab]
2009/06–2009/09	–1.83 ± 49.20[a]	–19.06 ± 36.19[a]	5.92 ± 7.33[a]	–22.62 ± 8.16[a]
2009/10–2010/06	31.76 ± 57.42[a]	0.59 ± 10.83[a]	25.41 ± 17.52[a]	2.10 ± 4.04[a]
2010/06–2010/09	111.05 ± 70.51[a]	24.62 ± 17.30[b]	22.74 ± 42.01[b]	9.92 ± 9.92[b]
Total leached in 2 years	193.11 ± 36.05[a]	50.74 ± 29.87[b]	63.36 ± 9.03[b]	15.23 ± 11.31[c]
Source of variation: treatment***; season***; treatment × season[ns]				

Lowercase letters in the same row indicate a significant difference in the different treatment ($P < 0.05$). The negative values were counted as zero in the total N leaching calculation of a 2-year study period; [ns]no significant difference; ***$P < 0.001$. CON – control; OMW – optimized winter wheat-summer maize double-cropping system with balanced N fertilization (manure and urea) and optimal water management; OFW – optimized winter wheat-summer maize double-cropping system with balanced N fertilization (urea only) and optimal water management; ORG – an organic alfalfa-winter wheat cropping system with low N and water input management

about 80 kg N/ha most of the time (Figure 3). Under this equivalency scenario, appropriate soil NO_3^--N concentrations are maintained not only to guarantee an appropriate N supply for the plant, but also to reduce the risk of NO_3^--N leaching (Cui et al. 2008a, Ju 2014). In our study, the improved measures in the optimized systems included converting excessive N fertilization to balanced N fertilization, changing flood irrigation to the optimized irrigation, returning straw to the field rather than burning it, substituting deep ploughing or no tillage for rotary tillage, reducing the amount of wheat sown and increasing maize planting density. These optimized cropping systems are potentially appropriate for NCP farmers and could reduce N fertilizer, water inputs and N leaching while maintaining grain yield.

In the organic system, N fertilizer input, water consumption and NO_3^--N leaching were reduced by 71, 43 and 92%, respectively, compared to the conventional system. However, grain yield declined by 46% (Tables 2–4). Number of recent studies have suggested that the grain yield of organic agriculture is often lower than in the conventional agriculture (de Ponti et al. 2012, Seufert et al. 2012). Identification of those factors limiting for grain yield in organic systems is important (Seufert et al. 2012). In the current research, NO_3^--N that accumulated in the root zone of the organic cropping system was less than 30 kg/N ha over most of the crop growth season (Figure 3). It has been suggested that NO_3^--N accumulation should be 87 kg N/ha (range of 66 to 118 kg N/ha) in order to achieve the best crop yields in the NCP (Cui et al. 2008b). In our experiment, relatively low NO_3^--N accumulation in the ORG system greatly reduced the NO_3^--N leaching risk, but decreased yield due to the concomitant N shortage, which suggested a significant disadvantage of the organic system. The main exogenous N in the organic system comes from manure and crop residues, and most of it exists in the form of organic compounds leading to be unavailable for crops until they are mineralized (Masoni et al. 2015, Arduini et al. 2018). In the organic cropping system, therefore, crop requirements for N during the critical growth stages are often asynchronous with N supply (Korsaeth 2008) because the N source has not yet been sufficiently mineralized; thus, a decrease in crop yield becomes inevitable.

The climate in the NCP is semi-moist and the yearly precipitation (500–600 mm) here is far less than the evaporation capacity (1100–2000 mm). The viewpoint that NO_3^--N leaching is little under these climate conditions has lasted for a long time (Yuan et al. 1995). However, it was proven that NO_3^--N leaching is the main pathway of nitrogen loss in this region, and the degree of leaching is largely determined by the precipitation or irrigation events (Fang et al. 2006, Wang et al. 2010). In a 2-year period, the soil surplus N in the winter wheat growing season accumulated in the form of nitrate in the 0–100 cm layer (Figures 2–3). Under these climate conditions, these accumulated nitrates were immobile, so even at managing with conventional measures the leaching was little (Table 4). On the other hand, although the rainfall is concentrated in the summer maize growing season (from June to September), the nitrate leaching

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degree still depends on the rainfall intensity. In the 2010 summer maize growing season, the heavy rainfall in the August caused the nitrate leaching in each treatment. Moreover, in this period there are high mineralization and nitrification potentials in soil. This enhanced the NO_3^--N leaching risk. Hence, the NO_3^--N leaching in summer is an N-loss pathway in this region and how to reduce the NO_3^--N leaching loss is a serious problem that deserves great concerns here.

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