Influences of irrigation and fertilization on soil N cycle and losses from wheat–maize cropping system in northern China

Xin Zhang, Guangmin Xiao, Roland Bol, Ligang Wang, Yuping Zhuge, Wenliang Wu, Hu Li, Fanqiao Meng

PII: S0269-7491(21)00434-6

DOI: https://doi.org/10.1016/j.envpol.2021.116852

Reference: ENPO 116852

To appear in: *Environmental Pollution*

Received Date: 5 November 2020

Revised Date: 17 January 2021

Accepted Date: 24 February 2021

Please cite this article as: Zhang, X., Xiao, G., Bol, R., Wang, L., Zhuge, Y., Wu, W., Li, H., Meng, F., Influences of irrigation and fertilization on soil N cycle and losses from wheat–maize cropping system in northern China, *Environmental Pollution*, https://doi.org/10.1016/j.envpol.2021.116852.

Author Statement

Dear Editor,

Individual contributions from each author to the paper are listed below:

Xin Zhang. Conceptualization, data curation, formal analysis, writing - original draft preparation.

Guangmin Xiao. Investigation, methodology, resources, software.

Roland Bol. Methodology, languages.

Ligang Wang. Methodology, resources.

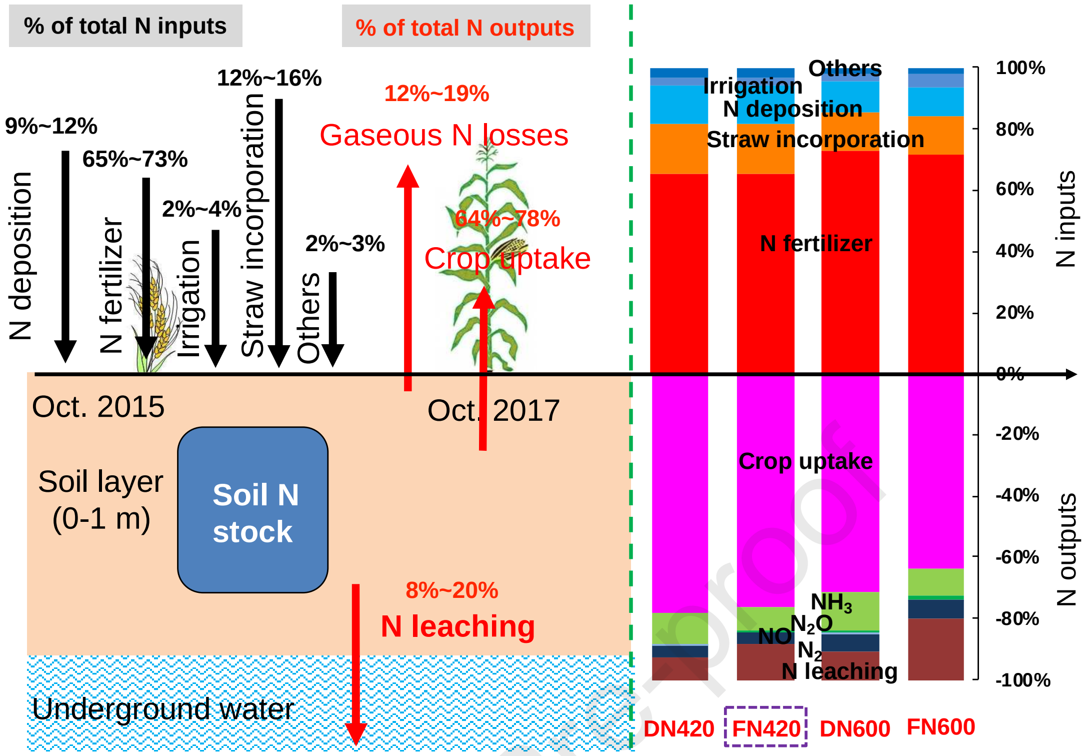
Yuping Zhuge. Methodology, resources.

Wenliang Wu. Methodology, resources.

Hu Li. Methodology, resources.

Fanqiao Meng. Supervision, writing - review & editing, funding acquisition.

Graphic abstract



Influences of irrigation and fertilization on soil N cycle and losses from wheat–maize cropping system in northern China

Xin Zhang[1, 2], Guangmin Xiao[2], Roland Bol[3, 4], Ligang Wang[5], Yuping Zhuge[6], Wenliang Wu[2], Hu Li[5], Fanqiao Meng[2*]

1 State Key Laboratory of North China Crop Improvement and Regulation, College of Resources and Environmental Sciences, Hebei Agricultural University, Baoding 071000, China

2 Beijing Key Laboratory of Farmland Soil Pollution Prevention and Remediation, Beijing Key Laboratory of Biodiversity and Organic Farming, College of Resources and Environmental Sciences, China Agricultural University, Beijing 100193, China

3 Institute of Crop Science and Resource Conservation, Soil Science and Soil Ecology, University of Bonn, Germany

4 School of Natural Sciences, Environment Centre Wales, Bangor University, Bangor, LL57 2UW, U.K.

5 Institute of Agricultural Resources and Regional Planning, Chinese Academy of Agricultural Sciences, Beijing 100081, China

6 National Engineering Laboratory for Efficient Utilization of Soil and Fertilizer Resources, College of Resources and Environment, Shandong Agricultural University, Taian, 271018, China

* Correspondence author. Email: mengfq@cau.edu.cn; Tell: 0086 10 62731538

Abstract

Excess of water irrigation and fertilizer consumption by crops has resulted in high soil nitrogen (N) losses and underground water contamination not only in China but worldwide. This study explored the effects of soil N input, soil N output, as well as the effect of different irrigation and N- fertilizer managements on residual N. For this, two consecutive years of winter wheat (*Triticum aestivum* L.) –summer maize (*Zea mays* L.) rotation was conducted with: N applied at 0 kg N ha^{-1} yr^{-1}, 420 kg N ha^{-1} yr^{-1} and 600 kg N ha^{-1} yr^{-1} under fertigation (DN0, DN420, DN600), and N applied at 0 kg N ha^{-1} yr^{-1} and 600 kg N ha^{-1} yr^{-1} under flood irrigation (FN0, FN600). The results demonstrated that low irrigation water consumption resulted in a 57.2% lower of irrigation-N input (p<0.05) in DN600 when compared to FN600, especially in a rainy year like 2015–2016. For N output, no significant difference was found with all N treatments. Soil gaseous N losses were highly correlated with fertilization (p<0.001) and were reduced by 23.6%–41.7% when fertilizer N was decreased by 30%. Soil N leaching was highly affected by irrigation and a higher reduction was observed under saving irrigation (reduced by 33.9%–57.3%) than under optimized fertilization (reduced by 23.6%–50.7%). The net N surplus was significantly increased with N application rate but was not affected by irrigation treatments. Under the same N level (600 kg N ha^{-1} yr^{-1}), fertigation increased the Total Nitrogen (TN) stock by 17.5% (0–100 cm) as compared to flood irrigation. These results highlighted the importance to further reduction of soil N losses under optimized fertilization and irrigation combined with N stabilizers or balanced- N fertilization for future agriculture development.

Keywords: fertigation; nitrogen cycling; soil N losses; winter wheat–summer maize rotation; northern China

Main findings:

Soil gaseous N (NH_3, N_2O, NO, etc.) emissions were highly simulated by N fertilization while nitrate leaching was mainly affected by irrigation measurement.

1 Introduction

Globally, fertilized croplands have been proved to be the major source of nitrogen pollutants, such as ammonia (NH_3), nitrous oxide (N_2O), nitric oxide (NO) and nitrate in water (Cui *et al.*, 2014a; Fan *et al.*, 2018). There is little doubt that fertilized croplands are substantial cause of driving the increase in soil nitrogen (N) losses (Yan *et al.*, 2015). Ammonia loss is highly correlated to N application rates and was reported to be around 3.2 Mg per year in China (Huang *et al.*, 2012). The overuse of N fertilizer in agriculture results in high soil N surplus (i.e., 200–400 kg N ha^{-1}) which is closely linked to N_2O and NO emissions (Ju *et al.*, 2006; Chen *et al.*, 2014). Nitrate is very mobile in soil and can be lost by leaching through water movement (Gioacchini *et al.*, 2002), resulting in heavy groundwater contamination. Accordingly, prevention of N losses through optimized farming practices especially in high intensity cropping systems is of great significance.

Northern China, the most important and intensified cereal crop production regions in China, is an area of annual winter wheat (*Triticum aestivum* L.)–summer maize (*Zea mays* L.) rotation cycle (Yan *et al.*, 2015). Unfortunately, intensive agricultural systems are still inefficient in N fertilizer use (around 50%–70% of fertilizer N is lost to the environment) (Ju *et al.*, 2009). Moreover, reactive-N losses (N_2O, NO, NH_3, NO_3^-–N leaching) possess potential pressures on underground water environment, air quality and regional or global GHG–driven climate change (Zhang *et al.*, 2020). In a semiarid area like northern China, crop yield, especially winter wheat is very dependent on irrigation pumped from deep groundwater (Zhang *et al.*, 2017). Heavy irrigation with low water use efficiency also causes NO_3^- to enter into deeper soils and groundwater or sometimes it is permanently lost (Currell *et al.*, 2012). Therefore, various farming measures have been taken since 1990s to reduce irrigation water and N fertilizer consumption, and maintain high crop yields, especially in northern China (Zhang *et al.*, 2019).

Drip irrigation, as an efficient irrigation and fertilization measure, contributes to high crop water- and N- use efficiency (Farneselli *et al.*, 2015). Nitrate leaching and N_2O/NO losses under fertigation were found to be lower than with furrow/flood treatments (Koocheki *et al.*, 2014; Maris *et al.*, 2015). The reasons might be 1) only a circular area wetted by the drippers has increased activities of nitrifying and denitrifying bacteria which stimulates N_2O and NO production (Trost *et al.*, 2014), and 2) highly efficient water and fertilizer utilization within root zone (Kennedy *et al.*, 2013). Despite the identified relationships between improved irrigation management and reduced nitrate leaching and N_2O emissions, knowledge about the soil N cycling, ammonia losses and NO losses under fertigation technology is still limited, especially in semiarid area like northern China. Although, a reduction of 11.0% in soil N_2O and increase of 14.7% in soil NO were found with fertigation during 2015–2016 as compared with farmers' practices (Zhang *et al.*, 2019), we are still interested in investigating the soil N balance including N input, N output and soil N stock changes to directly reveal the difference between irrigation/fertigation regimes.

In the following study, NH_3, N_2O and NO losses and soil N stock, as well as crop N uptake were measured simultaneously in wheat-maize rotation cycle in northern China. The aim of the present study is to: (1) determine which management events are beneficial for soil ammonia volatilization, N_2O and NO emissions and nitrate leaching over the cropping years, (2) assess the influence of irrigation/fertilization managements on soil N cycle and losses, (3) identify the potential changes in field managements to reduce N losses and maintain high crop yield.

2 Materials and methods

2.1 Study area and treatments

The study site (36°51′–37°06′N, 117°50′–118°10′E) was located in Huantai Experimental Station of China Agricultural University, Shandong province. Huantai County, the first one to achieve an average grain yield of 15 t ha^{-1} after 1990, was typically represented the farming system (an annual double crop rotation of winter wheat and summer maize form), geographical and climate conditions, irrigation and fertilization managements (Zhang et al., 2017). The mean annual precipitation and air temperature were 596.9 mm and 14.8 °C, respectively (Zhang *et al.*, 2020). The physio-chemical properties of the calcareous fluvo-aquic soil (0–30 cm) were as follows: bulk density- 1.40 g cm^{-3}; pH (1:2.5, soil/water)- 7.8; SOC concentration- 17.3 g kg^{-1}; and total N concentration- 1.1 g kg^{-1}.

The field study was conducted over 2 full cycles from Oct. 2015 to Oct. 2017 of the winter wheat (*T. aestivum* L.) and summer maize (*Z. mays* L.) cropping system.

Wheat (Luyuan 502) was sown in mid-October with a row space of 40 cm, and harvested in early June of the following year. Maize was sown in mid-June with a row space of 60 cm and harvested at the end of September. Previous maize and wheat straw were mechanically chopped (length of 5–8 cm and 2–5 cm, respectively) and then incorporated in the soil (Huang *et al.*, 2017).

In this study, two factors considered were irrigation management and N application rate. For both years, two irrigation management systems- drip irrigation (D) and flood irrigation (F), and three N application rates- 0, 420, and 600 kg N ha^{-1} yr^{-1} (referred to as no N application N0, optimal N application N420, and conventional N application N600) were conducted. In northern China, optimal N applied under flood irrigation has been much intensively studied during the past years with similar results and thus is not the subject of this experiment. The experimental design of current study included 5 treatments: DN0, DN420, DN600, FN0, and FN600, arranged in a randomized block design with three replications. Each plot was an area of 10 m length × 5 m width. The relevant N input and N output values of another flood irrigation treatment with N application rate at 420 kg N ha^{-1} yr^{-1} (FN420) are estimated in Table S1 in detail.

For drip irrigation, drip lines were installed along each crop row (total 12 lines for wheat and 8 lines for maize). Further details of surface drip fertigation system, time and amount of each irrigation, fertilization and rainfall in different crop growth stages for all treatments are described in a previous study (Zhang *et al.*, 2019). The total water received and soluble urea fertilizer used during 2015–2017 is represented in Figure 1.

2.3 Measurement of N_2O, NO and ammonia volatilization

N_2O and NO gas samples were collected using a closed chamber method, and were analyzed using a gas chromatograph (Agilent 7820A, Agilent, US) and a 42i chemiluminescence NOx analyzer (Thermo Environmental Instruments Inc., US), respectively. The N_2O and NO fluxes were determined by the linear or nonlinear methods (described in Supporting Information) (Yan *et al.*, 2015).

NH_3 was measured by Dräger-Tube Method, described in detail by Pacholski *et al.* (2008). The NH_3 concentration was recorded directly by Dräger detector tube

(Drägerwerk AG, Germany), which contained a solid phase acid compound and bromophenol blue pH indicator. The atmospheric pressure, air temperature, pump strokes and duration was recorded for the calculation of NH_3 fluxes (mg N m^{-2} h^{-1}) according to Eq. (1) (Pacholski *et al.*, 2006; Pacholski *et al.*, 2008):

$$F_{Ng}=V \cdot |conc.| \cdot 10^{-6} \cdot \rho_{NH3} \cdot U_N \cdot U_F \cdot U_Z \qquad (1)$$

where, F_{Ng} (mg N m^{-2} h^{-1}) is NH_3 volatilization flux; V (L) is pump volume; |conc.| (μl L, ppm) is NH_3 concentration; ρ_{NH3} (mg L^{-1}) is NH_3 density under the condition (ρ_{NH3}= 696 mg L^{-1}); U_N (14/17) is conversion factor of molecular weight from NH_3 to N; U_F (m^2, 10000/400) is surface area conversion factor; U_Z (h, 3600/time) is time conversion factor. NH_3 flux was then corrected according to wind speed at the height of 0.2 m and 2 m, as followed equations:

Wheat season:

$$\ln(NH_3\, flux_{IHF}) = 0.444 \cdot \ln(NH_3\, flux_{DTM}) + 0.590 \cdot \ln(V_{2m}) \qquad (2)$$

Maize season:

$$\ln(NH_3\, flux_{IHF}) = 0.456 \cdot \ln(NH_3\, flux_{DTM}) + 0.745 \cdot \ln(V_{2m}) - 0.280 \cdot \ln(V_{0.2m}) \qquad (3)$$

where, NH_3flux_{IHF} (kg N ha^{-1} h^{-1}) was determined by IHF method; V_{2m} and $V_{0.2m}$ (m s^{-1}) represent wind speed at the height of 2 m and 0.2 m, respectively.

2.3 Data calculation

To calculate N input, seven parameters were considered: N from fertilizer and irrigation water, straw incorporation, atmospheric deposition (dry and rainfall), non-bio fixation and seeds. All data were obtained as follows:

Fertilizer ($N_{Fertilizer}$)*, irrigation* ($N_{Irrigation}$) *and rainfall* ($N_{rainfall}$)*:* Across the two cropping years, N fertilizer application (urea- 46% N), irrigation and rainfall events are all shown in Figure 1. Irrigation water samples during each irrigation event, and rainfall samples during every rainy day were collected in cleaned plastic bottles and stored at −20°C for NH_4^+−N and NO_3^-−N concentration analysis using a continuous flow analyzer (TRAACS2000, SEAL Inc., Germany). The N input from irrigation and rainfall (kg N ha^{-1}) was determined according to NH_4^+−N and NO_3^-−N concentration (C; $mg\ L^{-1}$) and irrigation/rainfall amount (Q_1; mm):

$$N_{irrigation/rainfall} = (C_{NO3--N} + C_{NH4+-N}) \times Q_1 \times 10 \quad (4)$$

Straw incorporation: In this study, the N input of wheat straw incorporated in June 2015 was offset by the one incorporated in June 2017. Here, we did not consider the N input from previous straw incorporated before the maize season in Oct. 2015. During the experimental period, previous straw (wheat/maize) was collected and weighed for straw amount (Q_2; kg ha^{-1}) and then smashed to analyze the N content of straw (A_1; g kg^{-1}) by an element analyzer (Flash 2000, Thermo, US). The N input from straw incorporation (kg N ha^{-1}) was determined according to Eq. (5):

$$N_{Incorperation} = A_1 \times Q_2 / 1000 \qquad (5)$$

Atmospheric dry N deposition ($N_{Deposition}$): It is defined that gaseous and particulate N is transported from air to the surfaces of aquatic and terrestrial landscapes (Anderson and Downing, 2006). In northern China, atmospheric N (wet+dry) deposition has increased gradually from approximately 25 kg ha^{-1} in 1980s to around 80 kg ha^{-1} in 2010 (Ju *et al.*, 2009; Zhang *et al.*, 2011). Additionally, the wet N deposition (i.e., N input from rainfall) ranged from 19.5 to 28.8 kg ha^{-1} yr^{-1} (Table 1). And the dry N deposition was especially found up to 50 kg ha^{-1} yr^{-1} in northern China

(Liu *et al.*, 2020). Therefore, for the current work, we have set the value of annual dry N deposition in northern China at 55 kg N ha^{-1} (Shen *et al.*, 2009).

Non-bio fixation (*$N_{Fixation}$*)*:* It ranged from 4.5 to 20 kg ha^{-1} yr^{-1} for non-leguminous crops (Bouwman *et al.*, 2005). In the current work, we have set a value of 15 kg N ha^{-1} yr^{-1} for non-bio fixation in croplands (Liu *et al.*, 2008).

Seeds (*N_{seeds}*)*:* The maize and wheat seeds samples were collected and weighed. These were smashed to analyze the N content by an element analyzer (Flash 2000, Thermo, US). N input from seeds was calculated according to the sowing amount (kg ha^{-1}) and N content (g kg^{-1}) using Eq. (5):

For N output, we considered crop uptake, ammonia volatilization (N_{NH3}), and N_2O (N_{N2O}), NO (N_{NO}), N_2 (N_{N2}) emissions, and nitrate leaching. The calculation is presented below.

Crop uptake (*N_{Uptake}*)*:* Wheat and maize were harvested in each plot and the grain was separated from the straw. They were weighed after oven−drying to calculate the yield (grain/straw) and smashed to measure the N content. Crop N uptake by wheat and maize was determined by the grain/straw yield (kg ha^{-1}) and N content (g kg^{-1}) according to Eq. (5).

Ammonia volatilization (N_{NH3}), N_2O loss (N_{N2O}) and NO loss (N_{NO}): To more effectively assess the effect of the alternatives of irrigation and fertilizer managements on NH_3, N_2O and NO emissions, the annual cumulative losses were expressed on the area N bases (kg N ha^{-1}), and were calculated by summing the daily mean fluxes, and the one of nonmeasurement days which were estimated by interpolating linearly between sampling dates (Xu *et al*., 2020).

N_2 loss (N_{N2}): Houlton and Bai (2009) confirmed that N_2/N_2O ratio ranged from 2.2 to 4.6 at the global scale, while Ciarlo *et al.* (2006) reported a value of 4−9 during 21−day incubation period at 40%−80% of WFPS. Based on these previous studies, we set a seven-fold of N_2O emitted to evaluate N_2 loss.

Soil total N (TN): The soil samples (0−100 cm) were collected in triplicates from each plot in May 2013 (date of original experiment) and in Oct. 2017 and mixed into one composite sample. The subsamples were air dried and sieved through 0.5 mm mesh for soil total N concentration analysis with an element analyzer (Flash 2000, Thermo, US). The TN stock (kg N ha^{-1}) was calculated by Eq. (7),

$$TN\ stock = \sum_{i=1}^{5} \rho_i \times 0.2 \times 10000 \times c_i \qquad (7)$$

where, ρ_i is soil bulk density of ith soil layer (g cm^{-3}); c_i is TN concentration of ith soil layer (g kg^{-1}); i=1, 2, 3, 4, 5 represents 0−20 cm, 20−40 cm, 40−60 cm, 60−80 cm, and 80−100 cm soil layer, respectively.

N leaching (kg N ha^{-1}) was calculated as follows:

$$\text{N leaching} = (N_{Fertilizer} + N_{Irrigation} + N_{Deposition} + N_{Rainfall} + N_{Fixiation} + N_{Incorperation}) - (N_{Uptake} + N_{NH3} + N_{N2O} + N_{NO} + N_{N2}) - (TN_{Final} - TN_{Initial}) \times 2/4.5 \qquad (10)$$

where, $TN_{Initial}$ is the soil TN stock in May 2013; TN_{Final} is the soil TN stock in Oct. 2017.

2.5 Statistical analysis

In this study, all statistical analyses were performed using SPSS Statistics 22.0 software (SPSS Inc., Beijing, China). A t-test (p< 0.05) was used to determine the significant differences in total N input, crop N uptake, soil NH_3, N_2O, NO, and N leaching, and soil environmental variables between the treatments. All values were expressed as the mean (n=3) and standard error of each replicate.

3 Results

3.1 Soil nitrogen (N) stock

In this study, a 4.5 year (May 2013−Oct 2017) of soil TN stock in 0−100 cm soil layer was determined (Figure 2). Large variations were found in different soil layers, and the TN stock in 0−100 cm soil layer (especially in 0−60 cm) was significantly influenced by fertilization (Table 2).

In general, when flood irrigation was replaced with fertigation, soil TN stock (0−100 cm) was increased by 3.6% and 17.5% with N fertilizer applied at 420 kg N ha^{-1} yr^{-1} and 600 kg N ha^{-1} yr^{-1}, respectively (Table 1, Table S1). Additionally, with 30% reduction in N fertilizer, soil N stock was decreased by 48.0% under flood irrigation, while the respective reduction was by 54.2% under fertigation (Table S1). Furthermore, TN stock by DN420 and DN600 increased in 0−60 cm soil layer but decreased in deeper soil layers, while with FN600, TN stock increased in each soil layer (especially in 40−60 cm soil layer, Figure 2a2, b2, e2). From May 2013 to

October 2017, the increase in the amount of mean annual TN stock with different fertilized treatments varied in the following order: DN600> FN600> DN420 (186.2 kg N ha^{-1} yr^{-1}) in 0−60 cm soil layer and FN600 >DN600 >DN420 (–61.8 kg N ha^{-1} yr^{-1}) in 80−100 cm soil layer. This indicated that flood irrigation measurements might result in N movements to deeper soil layer.

3.2 N input and output

Over the two rotation years, chemical N fertilizer was estimated to contribute 65.3%−72.8% of total N input with all fertilization treatments (Table 1). As shown in Figure 3, during 2015−2016, irrigation N input by DN600 was 57.2% lower ($p<0.05$) than the one by FN600. N input with DN420 was the lowest due to a 30% reduction in N fertilizer application. During 2016−2017, a limit rainfall (decrease by 32.4% than the rainfall in 2015−2016) resulted in heavy irrigation water demand for fertigation, which increased irrigation N input. This led to no significant difference between N input by DN600 and FN600. N input by DN420 significantly decreased by 27.9% ($p<0.05$) and 23.1% ($p<0.05$) as compared to that by DN600 and FN600, respectively, in 2016−2017. In the 2 years, the N input by DN420 (1286.8 kg N ha^{-1}) was 21.9%

($p<0.05$) and 23.4% ($p<0.05$) lower than by DN600 and FN600, respectively (Table 1).

All fertilization treatments showed no significant difference in N output (Table 1, Figure 3). Compared with FN600, DN600 reduced N_2O and N_2 output by 11.4%, but increased NH_3 and NO output by 17.6% ($p<0.05$) and 14.2%, respectively, in 2015−2016. While, in 2016−2017, N_2O and N_2 output increased by 12.3% and that of NH_3 and NO increased by 24.3% and 26.9%, respectively. Under fertigation treatment, when there was a reduction of 30% in N fertilizer applied, 22.3% ($p<0.05$) of NH_3 output, 25.8% of N_2O output ($p<0.05$), 35.1% of NO output ($p<0.05$), and 25.8% of N_2 ($p<0.05$) output decreased when compared with DN600 treatment, in 2015−2016. While, in 2016−2017, 25.2% of NH_3 output ($p<0.05$), 49.1% of N_2O output ($p<0.05$), 40.6% of NO output ($p<0.05$), and 25.8% of N_2 output ($p<0.05$) decreased in comparison with DN600.

During the 2 consecutive cropping years, optimal fertilization treatments (DN420 and FN420) decreased NH_3, N_2O, NO emission by 23.6%−28.1%, 40.6%−41.7%, and 38.4%−40.6%, respectively, compared with conventional fertilization treatments

(DN600, FN600, Figure 4). Fertigation treatments (DN420, DN600) especially increased ammonia volatilization and NO emission by 20.5%−28.0% and 20.9%−29.7%, respectively, while decreased N_2O (/N_2) emission by 11.4%−12.8% in comparison with flood irrigation (FN420, FN600). Moreover, NH_3, N_2O and NO emissions were significantly stimulated by N fertilization especially in maize season (Table 2, 3). However, no significant interaction effects of irrigation and fertilization on season-/annual- NH_3, N_2O and NO emissions were detected in this study (Table 2). Allover, these results indicated a higher influence of fertilization on soil gaseous N losses than that of irrigation treatments.

3.3 Net N surplus and nitrate leaching

Net N surplus is defined as total N input minus N output, which reflects the increased amount of soil TN and increased nitrate (N) leaching. As shown in Figure 3, at the same N input, no significant difference with respect to net N surplus between fertigation and flood irrigation was observed. However, DN420 showed 48.7% ($p<0.05$, 153.3kg N ha^{-1}, 2015−2016) and 49.7% ($p<0.05$, 175.4 kg N ha^{-1}, 2016−2017) lower of net N surplus than with DN600.

N leaching (0−100 cm) plays an important role in soil N losses and is estimated by soil TN stock and net N surplus. Fertigation (DN420, DN600) was attributed to 33.9%−57.3% decrease in N leaching than flood irrigation (FN420, FN600) (Table 1, Table S1 and Figure 4). However, when N application was reduced by 30%, i.e. under optimal fertilization (DN420, FN420), 23.6%−50.7% of soil N was prevented from leaching compared with conventional fertilization (DN600, FN600). This indicated a higher influence of irrigation events on soil N leaching than fertilization treatments.

4 Discussions

4.1 Effects of irrigation and fertilization on soil gaseous N losses

Nitrogen fertilization greatly stimulated soil gaseous N (i.e., NH_3, N_2O and NO) emissions than irrigation measurements (Figure 4).

Ammonia volatilization is affected by the soil ammoniacal N concentration and by the resistance to NH_3 movement from soil matrix, which is highly correlated with soil NH_4^+ concentration (p<0.05, especially within 7 days after N application; Table S2) and significantly simulated by N fertilization (p<0.001, Table 2; Xu *et al.*, 2020). In this study, a 23.6%−28.1% reduction of NH_3 volatilization was found when N fertilizer applied was reduced by 30% (Figure 4). Immediate irrigation after fertilization causes the movement of fertilizer N into deeper soil layers, reducing the concentration of ammoniacal N in surface soil layer (Table S3; (Li *et al.*, 2018). For fertigation, urea was completely dissolved into irrigation water and then applied to crop system using a small irrigation water amount (<70 mm), which was beneficial in keeping the dissolved urea solution in top soil layer (Li and Rao, 2003). Li *et al.* (2018) reported that the activity of urease was improved and the hydrolysis of urea in fertigation occurred much more quickly than with other systems such as flood irrigation, especially under straw incorporation condition. Above all, a 20.5%−28.0% higher of NH_3 volatilization under fertigation than flood treatment was found in our study (Figure 4).

In agricultural soil, N_2O and NO emissions occurred within 7−14 days after fertilization or irrigation (Zaman *et al.*, 2008). Here, the water filled pore space (WFPS) during 7−days after irrigation with DN600 and FN600 was 68.4% and 77.8%, respectively (Table S3). Lower soil WFPS was beneficial in increasing O_2 concentration, and in promoting the oxidation of NH_4^+ to NH_2OH and NO_2^-, and then to NO_3^- (Zhou *et al.*, 2017). Meanwhile, N_2O produced by nitrification process could be further oxidized to NO, leading to higher NO production in fertigation (i.e. DN600) than in flood irrigation (FN600). Many previous studies have proved that NO is mainly ascribed to nitrification process (Tian *et al.*, 2016) and is highly correlated to soil NH_4^+−N ($p<0.05$) concentration but not to WFPS (Table 3). Additionally, nitrification mainly occurred when $NO/N_2O>1$ (Meijide *et al.*, 2007). After irrigation events, the NO/N_2O was >1 in the first 2−3 days under fertigation but a $NO/N_2O<1$ was observed under flood irrigation treatment (Figure S1). In northern China, nitrifier denitrification and nitrification were the main processes to stimulate N_2O emission, and accounted for 44%−58% and 35%−53% of total N_2O emission, respectively (Huang *et al.*, 2014). N_2O emission was highly correlated to NH_4^+−N ($p<0.01$), NO_3^-−N ($p<0.05$) and NH_4^+−N+NO_3^-−N ($p<0.01$) concentration (Table 3). This again highlighted that flood irrigation management is beneficial for the N_2O emission through nitrifier denitrification but inhibited the NO emission through nitrification (Tian *et al.*, 2016). Moreover, reduced fertilizer N application directly reduced the concentration of soil ammoniacal N, which highly contributed to gaseous N mitigation than saving irrigation water.

4.2 Alternative practices affecting residual soil N concentration

In a cropland, field management, soil pH, temperature, moisture, and texture, micro and macrofauna affect the residual soil N concentration (Malhi *et al.*, 2011). In northern China, no−tillage and straw incorporation are the main reasons resulting in increased soil N concentration (Liao *et al.*, 2015). Straw incorporation is a source of soil organic matter and crop N, and an energy source for soil microorganisms (Malhi *et al.*, 2011). Furthermore, straw incorporation with a high C:N ratio is beneficial in promoting the immobilization of N in soil by microbes (Luxhøi *et al.*, 2007). Also, no−tillage leads to higher net mineralization and nitrification rates but inhibits heterotrophic nitrification rates in upper soil layer (0−5 cm) (Liu *et al.*, 2017). Moreover, management-related losses of soil N pool were prevented and the conversion of soil N to readily available forms was observed to be reduced in untilled soil (Olin *et al.*, 2015).

In our study, fertigation increased the soil TN stock by 3.6%−17.5% (DN420, DN600) (Table S1) than the flood irrigation (FN420, FN600). First, lower soil moisture (Table S3) in fertigation treatments is proved to be beneficial for the activities of soil microorganisms and also promotes the N transformation from straw into soil N pool by net immobilization and mineralization. This increases the soil micro biomass, especially under straw incorporation condition (Bhat and Sujatha, 2009; Dignac *et al.*, 2017). Second, fertigation is observed to contribute towards soil N accumulation in 0−100 cm soil layer (especially in 0−60 cm) and significantly reduce the movement of N from surface soil layer to deeper layers (Figure S2; Halvorson *et al.*, 2008). This indicated the potential feasibility of applying alternative managements (i.e., fertigation combined with fertilizer N reduction) to prevent the movement of soil N to deeper.

4.3 Impact of fertigation on soil nitrate (N) leaching

N leaching is the main contributor of soil N losses, accounting for 10.1%−22.2% of N loss rates (Cui *et al.*, 2014b). Li *et al.* (2014) reported using DNDC model that the N leaching of farmers' practice was 128−132 kg N ha^{-1} yr^{-1} in flood irrigation. While, N leaching was 114 kg N ha^{-1} yr^{-1} when the N fertilizer applied was 600 kg N ha^{-1} yr^{-1}, according to the equation estimated by Chen *et al.* (2014). In our study, the N leaching value of 123 kg N ha^{-1} yr^{-1} of farmers' practice was observed which was in agreement with the previous studies. Reduced fertilizer- N application not only decreased soil gaseous N (NH_3, N_2O, NO, *etc.*) losses, but contributed to soil nitrate leaching reduction (Ju *et al.*, 2009). Abera *et al.* (2018) reported 7.2%−17.0% reduction in N leaching when 50% of fertilizer−N decreased. Our study highlighted that 23.6%−50.7% of N leaching was deceased when 30% of fertilizer N application was reduced (DN420 vs. DN600, FN420 vs. FN600; Figure 4).

As shown in section 4.1, saving irrigation managements i.e., fertigation was beneficial for nitrification processes, and contributed to the high accumulation of NO_3^-−N in soil under fertilized treatments especially in 0−60 cm soil layer (Figure S2−3; Cameira *et al.*, 2014). Soil N leaching was obviously influenced by irrigation measurements but not by fertilization (Figure 4; Yang *et al.*, 2018). For instance, Sui *et al.* (2015) reported that 15%−37% of N leaching was reduced in fertigation when 18%−36% of irrigation water was saved. Also, Peng *et al.* (2011) found that the N leaching was decreased by 38%−56% in control irrigation, as compared with flood irrigation. In the current study, N leaching was decreased by 33.9%−57.3% under fertigation as compared to that under flood irrigation with the same N level (DN420 vs. FN420; DN600 vs. FN600; Figure 4). Saving irrigation water measurement is thus a key factor to affect the soil N leaching to deeper soil layers than fertilization.

Although fertigation can highly reduce N leaching, the high residual N in the soil presents more potential risks to the environment than leaching (Sui *et al.*, 2015). Therefore, fertigation technology should be recommended coupled with alternative managements to reduce soil N losses and residual N. An example of the alternative technique include the use of urease/nitrification inhibitor combined with N fertilizer (urea) that could significantly reduce NH_3 volatilization, and N_2O and NO production (Zaman *et al.*, 2008; Zhao *et al.*, 2017). The balanced (reduced) N fertilization measurements were applied to decrease soil N pool (Zhang *et al.*, 2011). Although several such studies are reported, especially in northern China, more work needs to be done to develop better water and fertilizer saving technologies and meet the goal of sustainable agriculture development in future.

5 Conclusions

Drip fertigation can reduce the consumption of underground water for irrigation, which is beneficial for wheat−maize planting especially in semiarid area like northern China. Compared with 2015−2016, 32.4% decrease of rainfall caused 52.8% increase of irrigation- N input in 2016−2017. Under the same N application level, irrigation measurement was the key factor to affect soil N leaching (−33.9% − −57.3%) than fertilization (−23.6% − −50.7%). However, fertilization was the main factor to influence soil gaseous N losses (NH_3: −23.6% − −28.1%; N_2O: −20.8% − −41.7%; NO: −5.6% − −38.4%) than irrigation (NH_3: +20.5% − +28.0%; N_2O: −12.8% − −35.8%; NO: −21.2% − +20.9%). The net N surplus was significantly increased with N application rate but not affected by irrigation treatments, and the lowest one was found in DN420. Soil TN stock (0−100 cm) was increased by 3.6%−17.5% when flood irrigation was replaced with fertigation, while it was decreased by 48.0%−54.2% when N fertilizer application was reduced by 30%. To balance the influence of fertilization and irrigation on soil N losses, reducing the current irrigation water and N fertilizer N input would be the most promising alternative management practice in northern China. Moreover, N stabilizers or balanced- N fertilization and technologies should be studied and practiced to alleviate the high soil N losses for future agriculture development.

Acknowledgments

This study was financially supported by the State's Key Project of Research and Development Plan (2016YFD0201204). We also gratefully acknowledge the participating farmers at Huantai Experimental Station, and other relevant help.

References

Abera, D., Kibret, K., Beyene, S., Kebede, F., 2018. Nitrate leaching under farmers' fertilizer and irrigation water use in the central rift valley of Ethiopia. International Journal of Plant & Soil Science 21, 1-17. DOI: 10.9734/IJPSS/2018/39076

Anderson, K.A., Downing, J.A., 2006. Dry and wet atmospheric deposition of nitrogen, phosphorus and silicon in an agricultural region. Water, Air, and Soil Pollution 176, 351-374. DOI: 10.1007/s11270-006-9172-4

Bhat, R., Sujatha, S., 2009. Soil fertility and nutrient uptake by arecanut (Areca catechu L.) as affected by level and frequency of fertigation in a laterite soil. Agricultural Water Management 96, 445-456. DOI: 10.1016/j.agwat.2008.09.007

Bouwman, A., Van Drecht, G., Van der Hoek, K., 2005. Surface N balances and reactive N loss to the environment from global intensive agricultural production systems for the period 1970–2030. Science in China Series C: Life Sciences 48, 767-779. DOI: 10.1007/BF03187117

Cameira, M.R., Pereira, A., Ahuja, L., Ma, L., 2014. Sustainability and environmental assessment of fertigation in an intensive olive grove under Mediterranean conditions. Agricultural Water Management 146, 346-360. DOI: 10.1016/j.agwat.2014.09.007

Chen, X., Cui, Z., Fan, M., Vitousek, P., Zhao, M., Ma, W., Wang, Z., Zhang, W., Yan, X., Yang, J., Deng, X., Gao, Q., Zhang, Q., Guo, S., Ren, J., Li, S., Ye, Y., Wang, Z., Huang, J., Tang, Q., Sun, Y., Peng, X., Zhang, J., He, M., Zhu, Y., Xue, J., Wang, G., Wu, L., An, N., Wu, L., Ma, L., Zhang, W., Zhang, F., 2014. Producing more grain with lower environmental costs. Nature 514, 486-489. DOI: 10.1038/nature13609

Ciarlo, E., Conti, M., Bartoloni, N., Rubio, G., 2006. The effect of moisture on nitrous oxide emissions from soil and the $N_2O/(N_2O+N_2)$ ratio under laboratory conditions. Biology and Fertility of Soils 43, 675-681. DOI: 10.1007/s00374-006-0147-9

Cui, F., Zheng, X., Liu, C., Wang, K., Zhou, Z., Deng, J., 2014a. Assessing biogeochemical effects and best management practice for a wheat–maize cropping system using the DNDC model. Biogeosciences 11, 91-107. DOI: 10.5194/bg-11-91-2014

Cui, Z., Wang, G., Yue, S., Wu, L., Zhang, W., Zhang, F., Chen, X., 2014b. Closing the N-use efficiency gap to achieve food and environmental security. Environmental Science & Technology 48, 5780-5787. DOI: 10.1021/es5007127

Currell, M.J., Han, D., Chen, Z., Cartwright, I., 2012. Sustainability of groundwater usage in northern China: dependence on palaeowaters and effects on water quality, quantity and ecosystem health. Hydrological Processes 26, 4050-4066. DOI: 10.1002/hyp.9208

Dignac, M.F., Derrien, D., Barré, P., Barot, S., Cécillon, L., Chenu, C., Chevallier, T., Freschet, G.T., Garnier, P., Guenet, B., Hedde, M., Klumpp, K., Lashermes, G., Maron, P.A., Nunan, N., Roumet, C., Basile-Doelsch, I., 2017. Increasing soil carbon storage: mechanisms, effects of agricultural practices and proxies. A review. Agronomy for Sustainable Development 37,14. DOI: 10.1007/s13593-017-0421-2

Fan, C., Li, B., Xiong, Z., 2018. Nitrification inhibitors mitigated reactive gaseous nitrogen intensity in intensive vegetable soils from China. Science of the Total Environment 612, 480-489. DOI: 10.1016/j.scitotenv.2017.08.159

Farneselli, M., Benincasa, P., Tosti, G., Simonne, E., Guiducci, M., Tei, F., 2015. High fertigation frequency improves nitrogen uptake and crop performance in processing tomato grown with high nitrogen and water supply. Agricultural Water Management 154, 52-58. DOI: 10.1016/j.agwat.2015.03.002

Gioacchini, P., Nastri, A., Marzadori, C., Giovannini, C., Vittori Antisari, L., Gessa, C., 2002. Influence of urease and nitrification inhibitors on N losses from soils fertilized with urea. Biology and Fertility of Soils 36, 129-135. DOI: 10.1007/s00374-002-0521-1

Halvorson, A.D., Bartolo, M.E., Reule, C.A., Abdel, B., 2008. Nitrogen effects on onion yield under drip and furrow irrigation. Agronomy Journal 100, 1062-1069. DOI: 10.2134/agronj2007.0377

Houlton, B.Z., Bai, E., 2009. Imprint of denitrifying bacteria on the global terrestrial biosphere. Proceedings of the National Academy of Sciences 106, 21713-21716. DOI: 10.1073/pnas.0912111106

Huang, T., Gao, B., Hu, X.K., Lu, X., Well, R., Christie, P., Bakken, L.R., Ju, X.T., 2014. Ammonia-oxidation as an engine to generate nitrous oxide in an intensively managed calcareous fluvo-aquic soil. Scientific Reports 4, 3950. DOI: 10.1038/srep03950

Huang, T., Yang, H., Huang, C., Ju, X., 2017. Effect of fertilizer N rates and straw management on yield-scaled nitrous oxide emissions in a maize-wheat double cropping system. Field Crops Research 204, 1-11. DOI: 10.1016/j.fcr.2017.01.004

Huang, X., Song, Y., Li, M., Li, J., Huo, Q., Cai, X., Zhu, T., Hu, M., Zhang, H., 2012. A high-resolution ammonia emission inventory in China. Global Biogeochemical Cycles 26,GB1030. DOI: 10.1029/2011GB004161

Ju, X., Xing, G., Chen, X., Zhang, S., Zhang, L., Liu, X., Cui, Z., Yin, B., Christie, P., Zhu, Z., 2009. Reducing environmental risk by improving N management in intensive Chinese agricultural systems. Proceedings of the National Academy of Sciences of the United States of America 106, 3041-3046. DOI: 10.1073/pnas.0813417106

Ju, X.T., Kou, C.L., Zhang, F.S., Christie, P., 2006. Nitrogen balance and groundwater nitrate contamination: Comparison among three intensive cropping systems on the North China Plain. Environmental Pollution 143, 117-125. DOI: 10.1016/j.envpol.2005.11.005

Kennedy, T.L., Suddick, E.C., Six, J., 2013. Reduced nitrous oxide emissions and increased yields in California tomato cropping systems under drip irrigation and fertigation. Agriculture, Ecosystems & Environment 170, 16-27. DOI: 10.1016/j.agee.2013.02.002

Koocheki, A., Nassiri Mahallati, M., Moradi, R., Mansoori, H., 2014. Optimizing water, nitrogen and crop density in canola cultivation using response surface methodology and central composite design. Soil Science and Plant Nutrition 60, 286-298. DOI: 10.1080/00380768.2014.893535

Li, H., Wang, L., Qiu, J., Li, C., Gao, M., Gao, C., 2014. Calibration of DNDC model for nitrate leaching from an intensively cultivated region of Northern China. Geoderma 223-225, 108-118. DOI: 10.1016/j.geoderma.2014.01.002

Li, J., Rao, M., 2003. Field evaluation of crop yield as affected by nonuniformity of sprinkler-applied water and fertilizers. Agricultural Water Management 59, 1-13. DOI: 10.1016/S0378-3774(02)00123-3

Li, M., Wang, Y., Adeli, A., Yan, H., 2018. Effects of application methods and urea rates on ammonia volatilization, yields and fine root biomass of alfalfa. Field Crops Research 218, 115-125. DOI: 10.1016/j.fcr.2018.01.011

Liao, Y., Wu, W.L., Meng, F.Q., Smith, P., Lal, R., 2015. Increase in soil organic carbon by agricultural intensification in northern China. Biogeosciences 12, 1403-1413. DOI: 10.5194/bgd-11-16497-2014

Liu, C., Watanabe, M., Wang, Q., 2008. Changes in nitrogen budgets and nitrogen use efficiency in the agroecosystems of the Changjiang River basin between 1980 and 2000. Nutrient cycling in agroecosystems 80, 19-37. DOI: 10.1007/s10705-007-9118-2

Liu, S., Zhang, X., Zhao, J., Zhang, J., Müller, C., Cai, Z., 2017. Effects of long-term no tillage treatment on gross soil N transformations in black soil in Northeast China. Geoderma 301, 42-46. DOI: 10.1016/j.geoderma.2017.04.008

Liu, X.J., Xu, W., Du, E.Z., Tang, A.H., Zhang, Y., Zhang, Y.Y., Wen, Z., Hao, T.X., Pan, Y.P., Zhang, L., Gu, B.J., Zhao, Y., Shen, J.L., Zhou, F., Gao, Z.L., Feng, Z.Z., Chang, Y.H., Goulding, K., Collett, J.L., Jr., Vitousek, P.M., Zhang, F.S.,

2020. Environmental impacts of nitrogen emissions in China and the role of policies in emission reduction. Philosophical Transactions of the Royal Society A - Mathematical, Physical, and Engineering Sciences 378(2183), 20190324. DOI: 10.1098/rsta.2019.0324

Luxhøi, J., Elsgaard, L., Thomsen, I.K., Jensen, L.S., 2007. Effects of long-term annual inputs of straw and organic manure on plant N uptake and soil N fluxes. Soil Use and Management 23, 368-373. DOI: 10.1111/j.1475-2743.2007.00126.x

Malhi, S.S., Nyborg, M., Solberg, E.D., Dyck, M.F., Puurveen, D., 2011. Improving crop yield and N uptake with long-term straw retention in two contrasting soil types. Field Crops Research 124, 378-391. DOI: 10.1016/j.fcr.2011.07.009

Maris, S.C., Teira-Esmatges, M.R., Arbones, A., Rufat, J., 2015. Effect of irrigation, nitrogen application, and a nitrification inhibitor on nitrous oxide, carbon dioxide and methane emissions from an olive (Olea europaea L.) orchard. Science of the Total Environment 538, 966-978. DOI: 10.1016/j.scitotenv.2015.08.040

Meijide, A., Díez, J.A., Sánchez-Martín, L., López-Fernández, S., Vallejo, A., 2007. Nitrogen oxide emissions from an irrigated maize crop amended with treated pig slurries and composts in a Mediterranean climate. Agriculture, Ecosystems & Environment 121, 383-394. DOI: 10.1016/j.agee.2006.11.020

Olin, S., Lindeskog, M., Pugh, T.A.M., Schurgers, G., Wårlind, D., Mishurov, M., Zaehle, S., Stocker, B.D., Smith, B., Arneth, A., 2015. Soil carbon management in large-scale Earth system modelling: implications for crop yields and nitrogen leaching. Earth System Dynamics Discussions 6, 1047-1100. DOI: 10.5194/esdd-6-1047-2015

Pacholski, A., Cai, G., Nieder, R., Richter, J., Fan, X., Zhu, Z., Roelcke, M., 2006. Calibration of a simple method for determining ammonia volatilization in the field–comparative measurements in Henan Province, China. Nutrient Cycling in Agroecosystems 74, 259-273. DOI: 10.1007/s10705-006-9003-4

Pacholski, A., Cai, G., Fan, X., Ding, H., Chen, D., Nieder, R., Roelcke, M., 2008. Comparison of different methods for the measurement of ammonia volatilization after urea application in Henan Province, China. Journal of Plant Nutrition and Soil Science 171, 361-369. DOI: 10.1002/jpln.200625195

Peng, S., Yang, S., Xu, J., Luo, Y., Hou, H., 2011. Nitrogen and phosphorus leaching losses from paddy fields with different water and nitrogen managements. Paddy & Water Environment 9, 333-342. DOI: 10.1007/s10333-010-0246-y

Shen, J.L., Tang, A.H., Liu, X.J., Fangmeier, A., Goulding, K.T.W., Zhang, F.S., 2009. High concentrations and dry deposition of reactive nitrogen species at two sites in the North China Plain. Environmental Pollution 157, 3106-3113. DOI: 10.1016/j.envpol.2009.05.016

Sui, J., Wang, J., Gong, S., Xu, D., Zhang, Y., 2015. Effect of nitrogen and irrigation application on water movement and nitrogen transport for a wheat crop under drip irrigation in the North China Plain. Water 7, 6651-6672. DOI: 10.3390/w7116651

Tian, D., Zhang, Y., Mu, Y., Zhou, Y., Zhang, C., Liu, J., 2016. The effect of drip irrigation and drip fertigation on N_2O and NO emissions, water saving and grain yields in a maize field in the North China Plain. Science of the Total Environment 575, 1034-1040. DOI: 10.1016/j.scitotenv.2016.09.166

Trost, B., Klauss, H., Prochnow, A., Drastig, K., 2014. Nitrous oxide emissions from potato cropping under drip-fertigation in eastern Germany. Archives of Agronomy and Soil Science 60, 1519-1531. DOI: 10.1080/03650340.2014.903561

Xu, C., Han, X., Zhuge, Y., Xiao, G., Ni, B., Xu, X., Meng, F., 2020. Crop straw incorporation alleviates overall fertilizer-N losses and mitigates N_2O emissions per unit applied N from intensively farmed soils: An in situ ^{15}N tracing study. Science of the Total Environment, 142884. DOI: 10.1016/j.scitotenv.2020.142884

Yan, G., Yao, Z., Zheng, X., Liu, C., 2015. Characteristics of annual nitrous and nitric oxide emissions from major cereal crops in the North China Plain under alternative fertilizer management. Agriculture Ecosystems & Environment 207, 67-78. DOI: 10.1016/j.agee.2015.03.030

Li, Y., Li, J., Gao, L., Tian, Y., 2018. Irrigation has more influence than fertilization on leaching water quality and the potential environmental risk in excessively fertilized vegetable soils. Plos One 13, e0204570. DOI: 10.1371/journal.pone.0204570

Zaman, M., Nguyen, M.L., Blennerhassett, J.D., Quin, B.F., 2008. Reducing NH_3, N_2O and NO_3^--N losses from a pasture soil with urease or nitrification inhibitors and elemental S-amended nitrogenous fertilizers. Biology & Fertility of Soils 44, 693-705. DOI: 10.1007/s00374-007-0252-4

Zhang, F., Cui, Z., Fan, M., Zhang, W., Chen, X., Jiang, R., 2011. Integrated soil–crop system management: reducing environmental risk while increasing crop productivity and improving nutrient use efficiency in China. Journal of Environmental Quality 40, 1051-1057. DOI: 10.2134/jeq2010.0292

Zhang, X., Bol, R., Rahn, C., Xiao, G., Meng, F., Wu, W., 2017. Agricultural sustainable intensification improved nitrogen use efficiency and maintained high crop yield during 1980-2014 in Northern China. Science of the Total Environment 596-597, 61-68. DOI: 10.1016/j.scitotenv.2017.04.064

Zhang, X., Meng, F., Li, H., Wang, L., Wu, S., Xiao, G., Wu, W., 2019. Optimized fertigation maintains high yield and mitigates N_2O and NO emissions in an intensified wheat–maize cropping system. Agricultural Water Management 211, 26-36. DOI: 10.1016/j.agwat.2018.09.045

Zhang, X., Xiao, G., Li, H., Wang, L., Wu, S., Wu, W., Meng, F., 2020. Mitigation of greenhouse gas emissions through optimized irrigation and nitrogen fertilization in intensively managed wheat–maize production. Scientific Reports 10, 5907. DOI: 10.1038/s41598-020-62434-9

Zhao, Z., Wu, D., Bol, R., Shi, Y., Guo, Y., Meng, F., Wu, W., 2017. Nitrification inhibitor's effect on mitigating N_2O emissions was weakened by urease inhibitor in calcareous soils. Atmospheric Environment 166, 142-150. DOI: 10.1016/j.atmosenv.2017.07.034

Zhou, Y., Zhang, Y., Tian, D., Mu, Y., 2017. The influence of straw returning on N_2O emissions from a maize-wheat field in the North China Plain. Science of the Total Environment 584-585, 935-941. DOI: 10.1016/j.scitotenv.2017.01.141

Figure captions:

Figure 1 Fertilization, irrigation, rainfall events, total water received and cumulative nitrogen applied in fertilizer treatments during 2015–2017.

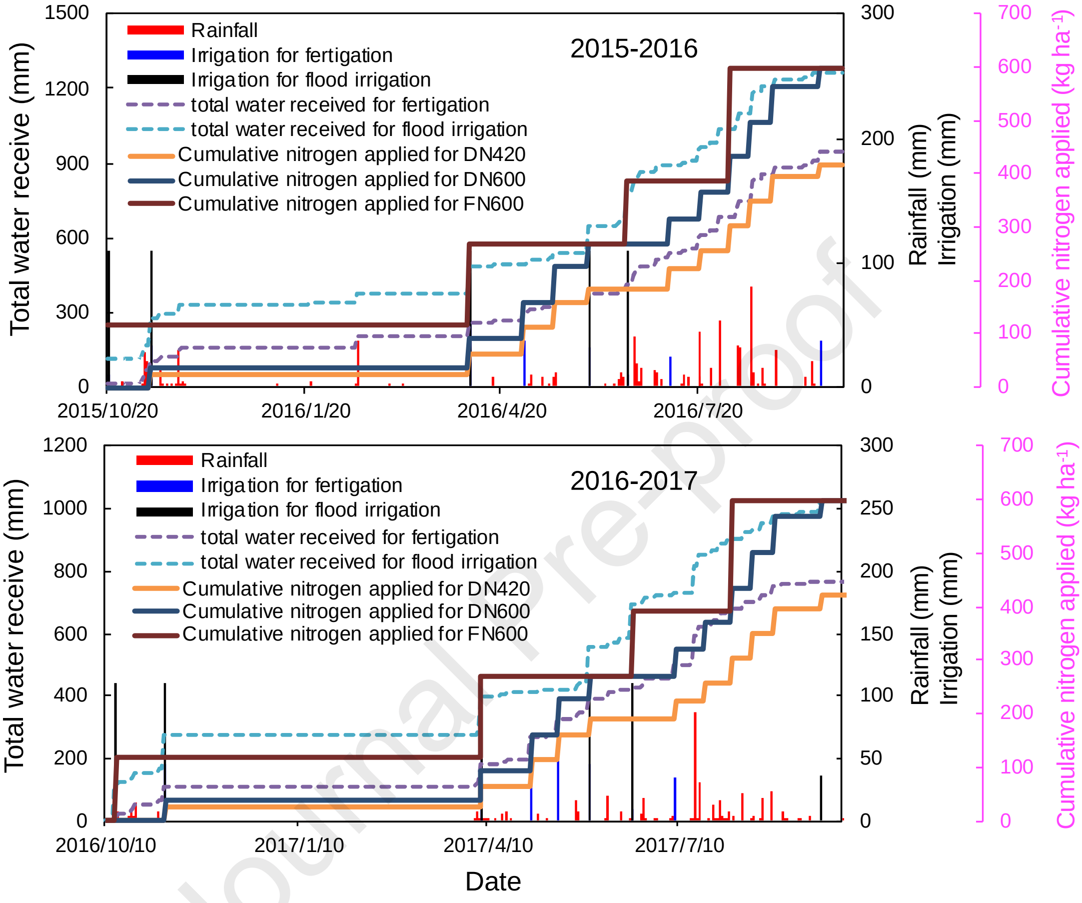
Figure 2 Changes of soil total N stock in 0−1m soil layer in (a1−2) DN0, (b1−2) FN0, (c1−2) DN420, (d1−2) DN600, and (e1−2) FN600. Error bars represent standard bars (n=3). Red background denotes soil TN accumulative, black background denotes soil TN loss. The experiment was conducted in May 2013 and our study was started in October 2017. DN0: drip fertigation without N fertilizer application; FN0: flood irrigation without N fertilizer application; DN420: optimal level of N fertilizer application and drip fertigation; DN600: conventional level of N fertilizer application and drip fertigation; and FN600: local farmers’ average level of N fertilizer application and flood irrigation.

Figure 3 N inputs, outputs, and net N surplus (total inputs-outputs) during 2015−2017 under DN420, DN600, and FN600. Note: Blue bars represent the standard error of total N inputs, red bars represent the standard error of total N outputs, black bars represent the standard error of net N surplus. Different letters above the bars indicate significant differences at $p<0.05$. Definitions of different fertilizer management regimes (i.e., DN420, DN600, and FN600) are given in caption of Figure 2.

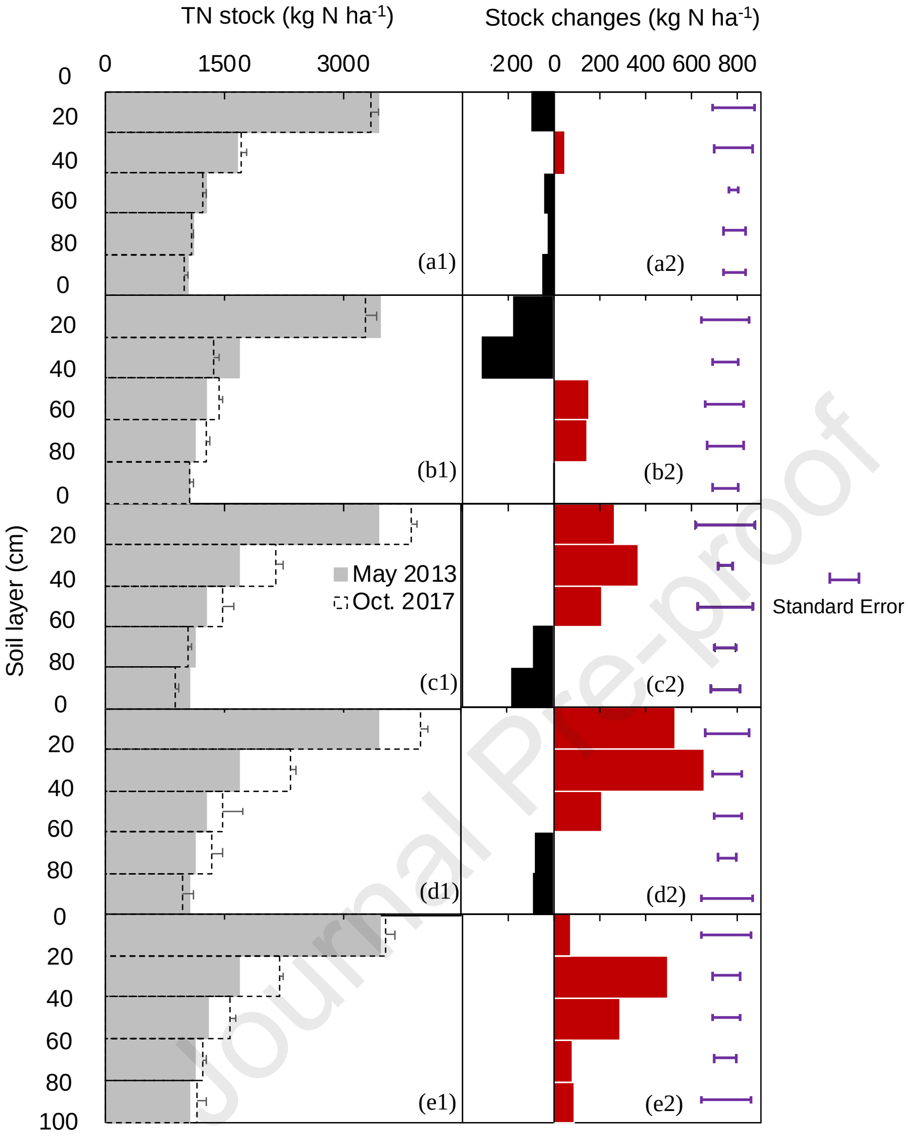
Figure 4 The reactive N losses under different fertilization and irrigation treatments. The relative data for FN420 (dashed line means the data was not monitored in situ) was estimated detailed in Table S1. Red value means the positive (reduction ratio) efficiency while blue value means the negative (increase ratio) efficiency. Means ± standard error.

Figures list:

Figure 1



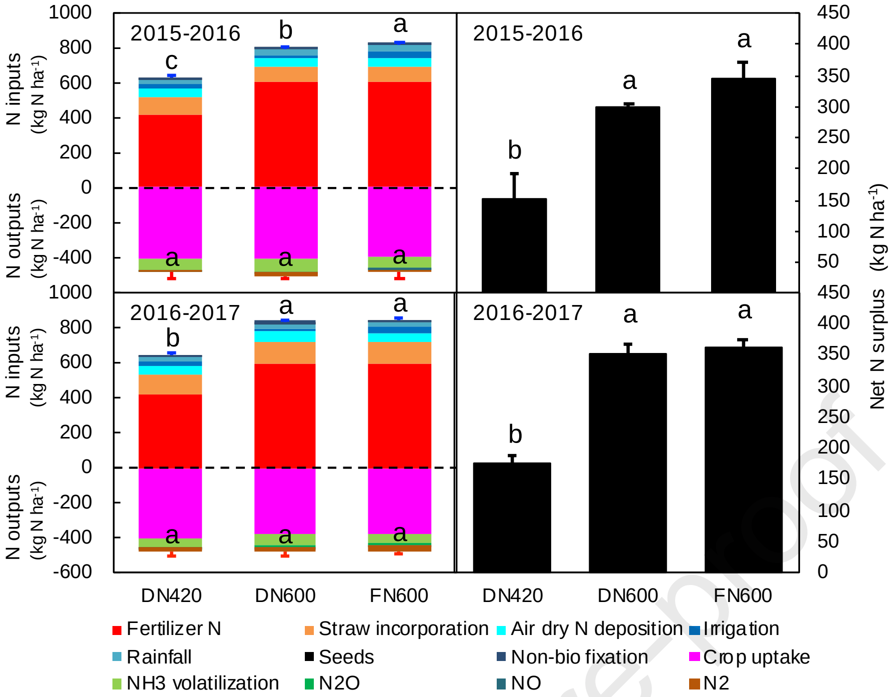
654 **Figure 2**



655

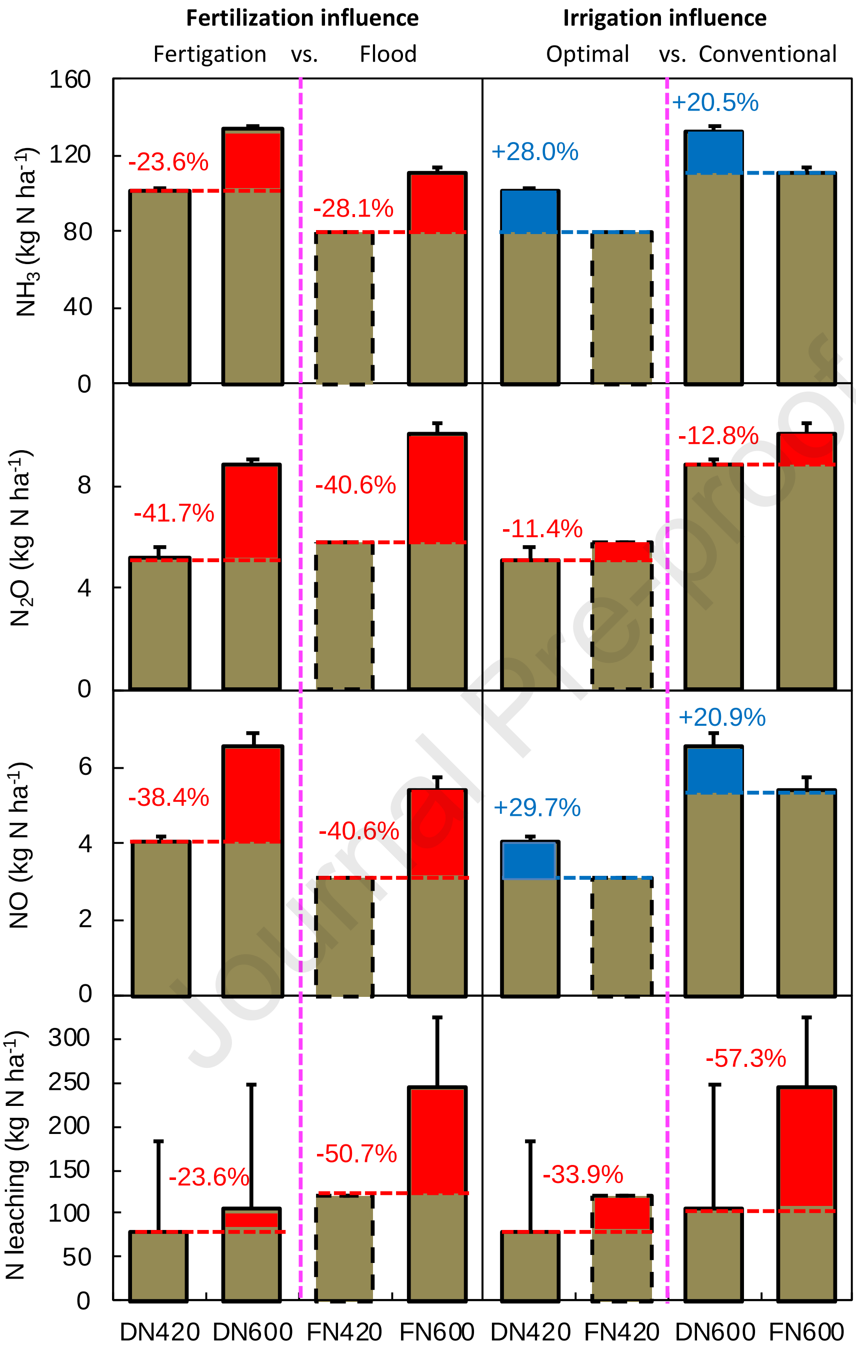
656

657 **Figure 3**



658

659 **Figure 4**



660

661

Tables list:

Table 1 Calculation of N balance under different fertilizer treatments in winter wheat−summer maize cropping system during 2015−2017.

Definitions of different fertilizer management regimes (i.e., DN420, DN600, and FN600) are given in caption of Figure 2.

	2015−2016 Winter wheat			2016 Summer maize			2016−2017 Winter wheat			2017 Summer maize			2 cropping years		
	DN420	DN600	FN600	DN420	DN600	FN600	DN420	DN600	FN600	DN420	N600	FN600	DN420	DN600	FN600
A: N inputs (kg N ha^{-1})															
Fertilizer N	189	270	270	231	330	330	189	270	270	231	330	330	840	1200	1200
Straw incorporation	77.2	69.8	73.9	19.8	19.1	18.9	84.0	89.6	88.0	28.4	32.4	27.3	209.4±11.6a	210.9±10.8a	208.1±15.5a
Dry N deposition	37	37	37	18	18	18	37	37	37	18	18	18	110	110	110
Irrigation	11.1	11.1	29.5	4.7	4.7	7.4	18.7	18.7	29.5	5.4	5.4	7.4	39.9	39.9	73.9
Rainfall	9.4	9.4	9.4	19.4	19.4	19.4	5.8	5.8	5.8	13.7	13.7	13.7	48.3	48.3	48.3
Seeds	4.4	4.4	4.4	0.2	0.2	0.2	4.4	4.4	4.4	0.2	0.2	0.2	9.2	9.2	9.2
Non-bio fixation	10	10	10	5	5	5	10	10	10	5	5	5	30	30	30
Total	338.1	411.7	434.2	298.1	396.4	398.9	348.9	435.5	444.7	301.7	404.7	401.6	**1286.8±11.6b**	**1648.3±10.8a**	**1679.5±15.5a**
B: N outputs (kg N ha^{-1})															
Crop uptake	188.5	185.4	177.4	217.6	222.5	217.1	196.4	191.9	189.6	208.5	190.2	191.5	811±63a	790±32a	776±36a
NH_3 volatilization	21.8	26.4	25.4	35.3	47.1	37.1	11.3	14.6	13.6	33.5	45.3	34.6	101.9±1.5c	133.4±2.7a	110.7±2.9b
N_2O	0.79	1.01	0.87	1.46	2.13	2.67	0.92	1.11	1.7	1.97	4.56	4.84	5.14±0.43c	8.81±0.19b	10.08±0.40a
NO	0.73	1.04	0.86	0.80	0.59	1.14	0.81	1.29	1.12	1.53	1.74	1.47	4.02±0.13c	6.53±0.36a	5.38±0.31b
N_2	5.53	7.07	6.09	10.2	14.9	18.7	6.44	7.77	11.9	13.8	31.9	33.9	36.0±3.0c	61.7±1.3b	70.6±2.8a
Total	214.3	217.9	207.5	260.6	283.3	271.9	212.9	212.9	214.2	253.3	253.9	247.0	**958.1±58.7a**	**1000.5±31.2a**	**972.3±39.6a**
C: Increased amount of TN	-	-	-	-	-	-	-	-	-	-	-	-	**248.8±58.7a**	**543.1±154.0a**	**462.1±76.8a**

(kg N ha^{-1})															
D: N leaching (kg N ha^{-1})	-	-	-	-	-	-	-	-	-	-	-	**-**	**79.9±103.1a**	**104.6±144.0a**	**245.0±79.6a**

Table 2 Two-way ANOVA of the effects of irrigation and N fertilization on seasonal-/annual- NH_3 volatilization, N_2O and NO emissions. *, ** and *** represent the 0.05, 0.01 and 0.001 significance levels, respectively.

	Wheat season			Maize season			Annual				
	NH_3 volatilization	N_2O emissions	NO emissions	NH_3 volatilization	N_2O emissions	NO emissions	NH_3 volatilization	N_2O emissions	NO emissions	N leaching	Soil TN stock
Irrigation	0.0029**	0.3744	0.1174	0.0000***	0.0329*	0.0004***	0.0000***	0.0041**	0.0033**	0.3777	0.6354
Fertilization	0.1459	0.2719	0.0028**	0.0000***	0.0062**	0.0001***	0.0000***	0.0001***	0.0000***	0.4657	0.0218*
Irrigation×Fertilization	0.7996	0.9184	0.4587	0.9818	0.8840	0.1208	0.9165	0.3383	0.5435	0.6226	0.7008

Table 3 Relationship between N_2O, NO, NH_3, N_2O+NO fluxes and soil NH_4^+−N, NO_3^-−N, NH_4^+−N+NO_3^-−N concentration in 7 days after N fertilization and irrigation events. Symbols of * and ** stand for significant at p<0.05 and p<0.01, respectively.

	N_2O flux	NO flux	N_2O+NO fluxes	NH_3 flux
NH_4^+-N	0.443**	0.345*	0.410**	0.323*
NO_3^--N	0.339*	0.165	0.251	-.314*
NH_4^+-N+NO_3^--N	0.443**	0.262	0.357*	0.380**
WFPS	0.096	-0.222	-0.134	-0.100

HIGHLIGHTS

- Soil N residual was accumulated in top soil under fertigation
- Gaseous N emissions were highly stimulated by N fertilization
- N leaching was mainly affected by irrigation but not N fertilization measurement
- DN420 significantly decreased soil N losses and achieved a higher crop N uptake

Conflict of interest:

The authors declared that there have no conflicts of interest to this work.