

POTENTIAL FOR NITROUS OXIDE EMISSION MITIGATION FROM SPRINKLING IRRIGATION APPLICATIONS OF CHEMICAL FERTILIZER COMPARED TO FURROW IRRIGATION IN ARID REGION AGRICULTURE

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Abstract. Sprinkling water is applied in shorter irrigation intervals and lighter irrigation applications in arid areas. The water-saving irrigation is the primary method of local agricultural production. Since chemical fertilizer is the primary emission source of nitrous oxide (N₂O), it is appropriate to verify the general influence of water-saving irrigation on N₂O. Results of the study, conducted in a potato field as the experimental site for two consecutive years, using two different irrigation systems – namely, furrow (FI) and sprinkling-irrigation (SI) with a mineral N fertilizer (NF) and a control without any fertilizer (Control) are reported. The N₂O emission fluxes with NF were higher than those of the control in each irrigation system. On plots where the NF was applied, mean emissions fluxes of N₂O was 152.02 μg/(m² hr) in FI, 36.53 μg/(m² hr) in SI from 2016 to 2017. The reduction of N₂O emissions from SI was due to the lower amount of water applied every time and the lower NO₃⁻-N and NH₄⁺-N of soil associated with SI. This work showed that SI is a method that helps save water and mitigates emissions of the atmospheric N₂O pollutants compared to FI.

Keywords: *greenhouse gas, moisture, fertilization, emission factor, potato field*

Introduction

Nitrous oxide (N₂O) is one of the most significant long-lived greenhouse gases in the atmosphere. The atmospheric N₂O concentration has increased from 270 ppbv (10⁻⁹ volume ratio) in 1750 to 324 ppbv in 2011, resulting in an increase of 0.17 W/m² in radiative forcing. Especially from 2007 to 2011, N₂O concentration in the atmosphere increased linearly at an annual average rate of 6% (IPCC, 2013; Schilt et al., 2014). Agricultural production is the primary source of N₂O emission (Robertson et al., 2000). Agricultural emissions accounted for about 56% of the total anthropogenic atmospheric N₂O emissions in 2005 (US-EPA, 2006). The water strategy is one of the essential factors that affect the emissions of N₂O from agricultural soils. In irrigated soils, the amount of water used and its distribution in the soil influence moisture temporally and spatially. Consequently, different moisture content determines the processes that control

the amount of N transported, N mineralized such as NO_3^- -N leaching within the soil. The changes on water and nitrogen in the soil affect the temporal and spatial distribution for various forms of nitrogen and the formation of N_2O . These irrigating systems, for instance, furrow (FI) or sprinkling irrigation (SI), significantly influence the movement of water in the soil because vertical and lateral infiltration are produced simultaneously (Auxiliadora et al., 2018; Naghedifar et al., 2018).

In arid and semiarid areas, FI is one of the most traditional surface irrigation systems because many crops that do not grow in water for long periods are suitable for this irrigation method. Under FI, water is delivered into each strip at a high amount from a head at its upper end to promote the rapid dissolution of fertilizers because of soaking in large quantities of water (Naghedifar et al., 2018). After the irrigation with long intervals and heavy application depths, water flows through the macropores, and most of the soil volume is wetted, temporarily creating the high ratio of anaerobic microsites, even if the small ratio of the ridge top may remain dry.

SI is one of the most popular methods of irrigation worldwide as an efficient and economically viable alternative (Ezequiel et al., 2018), because it offers the precise controlling of irrigation water amount and uniformity to decrease water and N losses (Lorenzo et al., 2018; José et al., 2018). Sprinkling water is applied on shorter irrigation intervals and lighter irrigation applications. Canopy induced irrigation water redistribution, which influenced the spatial and temporal variability of water in the soil. Irrigation water reaches the surface of the soil after it passes through the developed crop canopy, like precipitation. The wetted front in the soil surface moves downward under capillarity action and only a small part of the soil volume is nearly saturated due to the uniformity of irrigation (Naghedifar et al., 2018; Zapata et al., 2018). The wetted front from the soil surface advances slightly into the soil during sprinkling irrigation (Laura et al., 2008). Consequently, increasing the amount of water from different irrigation systems increases the wetted volume and shape in the soil, which mainly depends on the quantity and rate of applied water. The hydraulic properties in the irrigated soil determine the horizontal and vertical infiltration of water (Li et al., 2003; Vázquez et al., 2005). In previous studies, although the influences of moisture on crop growth have been very well recorded in SI and FI systems (Davidson, 1991; Granli and Bockman, 1994), the effects of these different wetted patterns in the soils on N_2O emissions are not known. So far, the information on N_2O emissions and the related importance do not appear in the comparison between sprinkling and furrow irrigation soils.

We assumed that the irrigation methods will influence N_2O emissions because of the different wetted forms in the furrow and sprinkling irrigation soils. In the sprinkled soil, the applied water at low water amount may be beneficial to more aerobic than anaerobic environment. The advance of the wetting front may produce pulses of N_2O from the furrow-irrigated areas, similar to those observed after irrigation when soil was dry (Diego et al., 2017). Therefore, we doubt that the differences of water distributed between SI and FI soils may occur the different states in N_2O emissions. In our studies, the objectives were to compare N_2O emissions in the soils from a potato field with furrow and sprinkling irrigation, and to assess how the two irrigation systems modulated the N_2O emissions and emission factor of N_2O . In this experiment, the results would help to develop the strategies to mitigate N_2O emissions from the soils fertilized with chemical fertilizers in irrigated agriculture.

Materials and methods

Description of the study site

The experiment was implemented during the 2016–2017 at the potato experimental farm in the suburbs of Hohhot, Inner Mongolia (latitude 40°45'34"N, longitude 111°41'56"E), in the middle of Inner Mongolia Plateau located in the hinterland of the Asian continent (*Fig. 1*). The soil was a Calcic Haploxerept with a sandy clay loam texture (Soil Survey Staff, 1992). Some physico-chemical properties in the upper (0–30 cm) horizon of the soil were: pH, 7.79; organic matter, 0.93 ± 0.2 g/kg; bulk density, 1.25 ± 0.2 g/cm³; clay, 32%; silt, 20%; and sand, 48%; CaCO₃, 8.54 ± 0.1 g/kg. The mean annual precipitation is 335 mm and the mean annual temperature is 6.7 °C (averages for the previous 15 years).



Figure 1. The experimental site and equipments used to collect gases in the potato field

Experimental design and field management

The experiment was arranged according to a split-plot design. Two main plots (600 m²) were selected in the experimental field with two treatments. Every main plot was divided into six subplots (5×10 m) in a randomized complete block design with three replicates. The main-plot treatments were different irrigation systems: furrow and sprinkling irrigation. Each mainplot was also split according to the fertilizer treatment applied: (i) N, P, and K compound fertilizer and urea as a chemical fertilizer (NF, 390 kg N/ha) and (ii) a control without any fertilizer (Control). The amount of applied fertilizer is the local range used by farmers for potato crops (360–410 kg N/ha). Fertilizers were applied by hand and immediately incorporated into the upper 15 cm of the soil using a rotovator. Sprinkling irrigation is often used to apply soluble fertilizers, in small amounts, as and when irrigated. Per subplot included five pressure-compensated sprinkling irrigation lines spaced 90 cm apart. Each sprinkling irrigation line was fitted with a solid set consisting of six full circle impact sprinklers (Elgo 80B2, made in Israel) with a wetting radius of 10 m, spaced 2.8 m apart, mounted on 1.30 m risers. A water meter (LXS-20C, TEFEN Manufacture, Nahsholim, Israel) was installed in the main pipe to measure sprinkling water amount in each experimental plot. This method is a popular practice in local farmers.

The experimental site for the furrow irrigation involved five furrows in each subplot, which were spaced 90 cm apart and ploughed 30 cm deep. The furrows were enclosed at the end of each experimental site, as irrigation water was intercepted to prevent it from flowing out of the field. The subplots were independent, but irrigated at the same time. The furrows were constructed using a seeding machine. The amount of used

irrigation water was recorded by water meter on each irrigated subplot after fertilizer application.

A potato crop (*Solanum tuberosum* L. cv. *Favorita*) requiring about 105 days to reach maturity was planted by potato seeder on May 25th, 2016 and May 15th, 2017. The potatoes were planted on the raised beds 0.3 m high and 0.6 m wide, with the top of 0.3 m bed wide and with a 0.20 m spacing between plants in a row and sowing rate of 2250 kg/ha. The time for potatoes to be harvested is September.

Irrigation management

The first irrigation began on May 25th, 2016 and May 15th, 2017, immediately after the potatoes were planted. Water application intensity in the first was 40 mm for sprinkling irrigation. After the potatoes revived, the sprinkling field was irrigated when the mean soil matric potential (SMP) of the 0–20 cm soil layer decreased to about –24.5 kPa. The distribution of main potato-root zones determined the irrigation duration, which was usually about 1.5 min, with about 10 mm of water each time at a pressure of 0.1 Mpa by automatic control with computer. Sprinkling irrigation was stopped 20 d before harvesting.

The date and water amount of furrow irrigation were implemented based on local irrigation practices. Irrigation was uniformly applied three times throughout the crop growing season: once when potatoes were planted and the second in the tuber set stages and third time during the tuber bulking stages. The amount of water applied at each irrigation event was about 200 mm. The total amounts of water applied for sprinkling and furrow irrigation during the study period were 200.7 and 601.8 mm in 2016, 205 and 593.7 mm in 2017, respectively. Sprinkling irrigation frequency was higher, while total irrigation water was smaller in the sprinkling-irrigated field than in the furrow irrigated field in the experimental seasons. Sprinkling irrigation always characterizes by the higher frequency with a smaller quota for each event respected to furrow irrigation. Total precipitation was less than 200 mm during the crop growing season.

Sampling and analysis of N₂O

The N₂O fluxes were measured in situ simultaneously from each sprinkling irrigation and furrow irrigation plot using a static opaque chamber method (Yang et al., 2018). The chamber headspace was a 125 l cube (50 cm × 50 cm × 50 cm). The outer layer of the chamber was covered with sponge and aluminum foil, which is used to prevent the chamber from being heated by sunlight. The chambers were placed inside the square stainless-steel rings (50 cm × 50 cm) to ensure a good seal without destroying the compactness of the soil. The square stainless-steel rings were inserted into the soil, to a depth of 15 cm. On a day before sampling the gas samples, those rings were taken in order not to disturb the water distribution during irrigation. The chambers were closed for 60 min between 8:00 a.m. and 9:00 a.m. During this time, N₂O concentrations increased linearly. At 0 min, 5 min, 10 min, 15 min, and 20 min, the gas samples (100 ml) were collected in evacuated three-part polypropylene syringes, respectively. They were taken once per week throughout the potato growing season from planting to harvesting. The air temperature inside the chambers was observed during collecting sample. Soil temperature was monitored in the field using a portable digital thermometer (JM 624, JinMing Instrument Co. Ltd., Tianjin, China) inserted into the

soil: the monitored data were stored in a data logger. The moisture of soil was measured by the TDR350-indicating instrument (SPECTRUM Inc., ST Petersburg, Florida, USA).

The N₂O in the samples were measured and analyzed within 12 h by gas chromatograph (Agilent 6820D, Agilent Corporation, Shanghai, China) that was used two detectors: an electron capture detector (ECD) and a hydrogen flame ionization detector (FID). Its configurations described by Jiao (2015) were implemented for the N₂O analysis (Jiao et al., 2015).

Soil analysis

After sampling the gas, the soil in each stainless-steel ring was simultaneously collected and soil NO₃⁻-N and NH₄⁺-N were determined by extracting 8 g of fresh soil with 60 ml of deionized water and 50 ml of KCl (0.01 M), respectively. They were measured using a micro-Kjeldahl procedure (Aulakh et al., 2000). SOC was determined by analysing soil extracts using a TOC analyzer (Sievers 5310 C, GE Analytical Instruments, USA) (Lim and Choi, 2014). Precipitation data were collected from the portable weather station located in the potato experimental farm.

Calculation method of N₂O emissions

Fluxes of N₂O was estimated within the closed chamber from the linear increase of gas concentration over sampling time of 0 min, 5 min, 10 min, 15 min, and 20 min based on $r^2 \geq 0.90$ while providing the maximum available flux data in the analysis of gas emissions (Jiao et al., 2015). Gas concentrations were converted to mass per unit volume ($\mu\text{g N}_2\text{O}/\text{uL}$) using the Ideal Gas Law at chamber air temperature measured during each sampling event and 0.101 MPa. Fluxes of N₂O were computed as:

$$F = \frac{\Delta C}{\Delta t} \times V/A \times \alpha \quad (\text{Eq.1})$$

where F is the flux rate of N₂O ($\mu\text{g N}_2\text{O-N}/(\text{m}^2 \text{ hr})$), $\Delta C/\Delta t$ denotes the increase or decrease of gas concentration in the chamber ($\mu\text{g}/(\text{L h})$), V is the volume of the chamber (L), A is the covered surface area (m^2), and α is a conversion coefficient for elemental N (28/44 for N₂O) (Eq. 1). Gas fluxes which failed linearity test were not included in the data analysis and accounted for < 2% of the total data set, while gas fluxes that failed significance and detection tests were set to zero flux. A complete discussion of chamber flux method is described in (Adviento-Borbe and Linquist, 2016).

Data statistics and analysis

The N₂O emissions were estimated by successive linear interpolation of N₂O emissions from the soils associated with the different irrigation systems. Statistical analyses were performed using SPSS version 22.0 (SPSS Inc., Chicago, IL, USA). A one-way analysis of variance (ANOVA) was used to evaluate the differences in seasonal and annual cumulative emissions of N₂O between the different irrigation. Tukey's multiple range tests were used to determine whether significant differences occurred between the treatments at a significance level of 0.05. A two-way ANOVA was used to analyze the effects of treatments and their interactions on N₂O emissions. Data drafting was run by SigmaPlot 13 and Excel 2016.

Results

Changes in precipitation and temperatures

The frequency of rainfall in crop growing season in 2016 is higher than that in 2017. There was no significant difference in the total rainfall of the crop growing season in 2016 and 2017 ($p > 0.05$), which were 196.6 mm and 198.8 mm, respectively. The atmospheric temperature showed a consistent trend of change from May to September in 2016 and 2017. The temperature began to increase gradually in April and was higher from July to August than other months (*Fig. 2*).

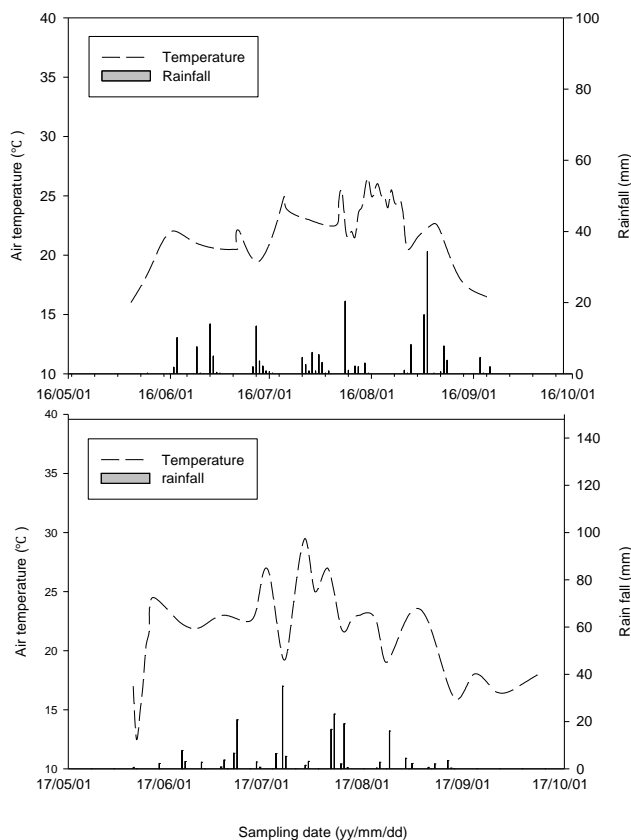


Figure 2. Variable amount of temperature and precipitation in the potato experimental farm in 2016 and 2017

Variation relationship between N₂O emission fluxes and the moisture or temperature in the soils of SI and FI

The potato field under four treatments from sprinkling irrigation systems and furrow irrigation systems exhibited a similar trend in N₂O emission fluxes. A significant emission peak of N₂O was detected in July and August throughout the testing stage from 2016 to 2017 (*Fig. 3*). Both the chemical fertilizer applied and the irrigation methods used affected the N₂O emission fluxes (*Fig. 3*). The NF soils from SI exhibited the highest N₂O emission fluxes, with 613.5 $\mu\text{g}/(\text{m}^2 \text{ hr})$ in July 2017. The highest N₂O emission fluxes were produced with 1047.9 $\mu\text{g}/(\text{m}^2 \text{ hr})$ from FI in the NF soils in July 2017. For the fertilization treatment and control under furrow irrigation system, the N₂O fluxes observed were higher than that in the sprinkling irrigation system in two crop

growing seasons, respectively. The N₂O emission fluxes of the fertilization treatment were higher than those of the control treatment in each irrigation system during the experimental period (Fig. 3).

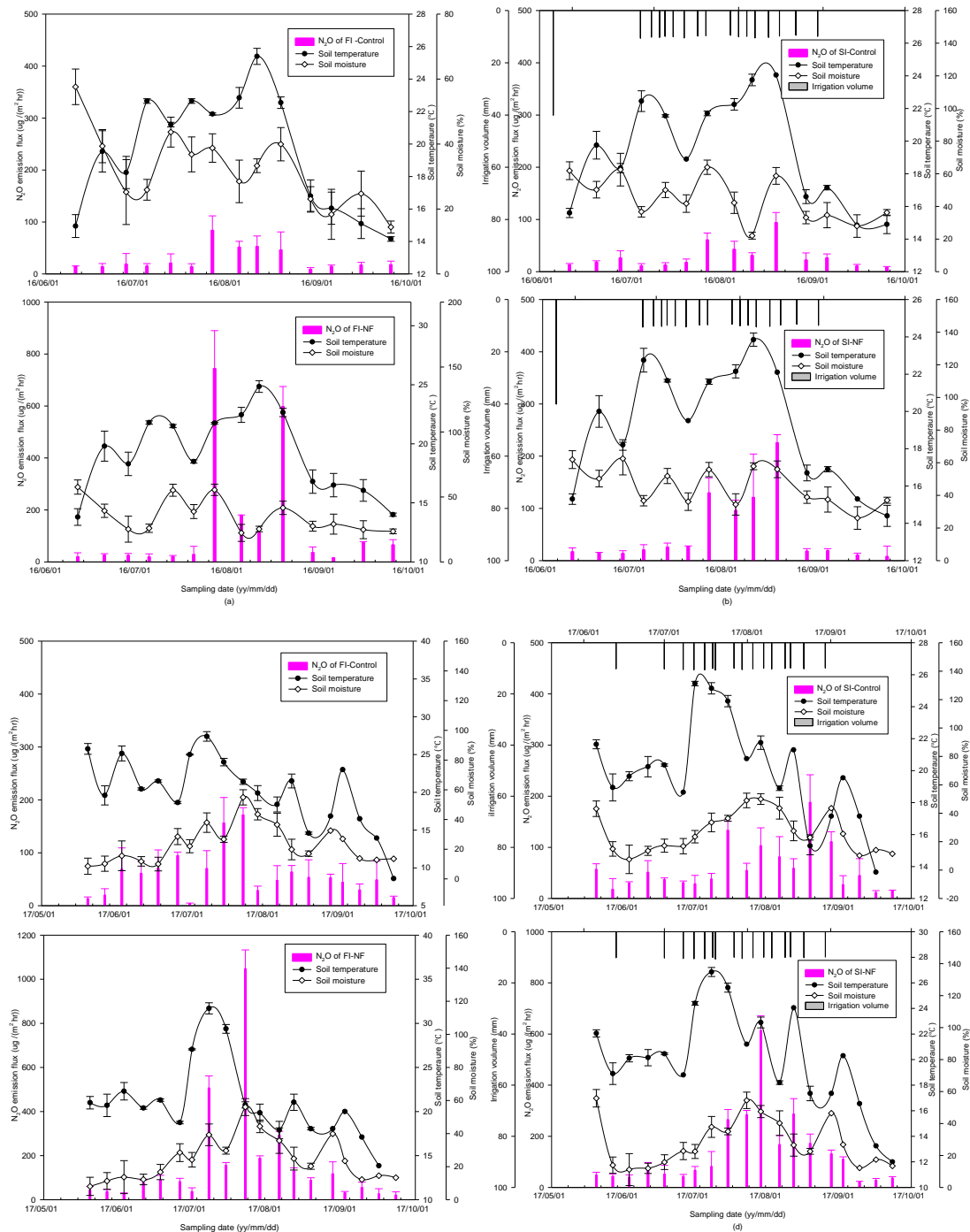


Figure 3. Variation relationship between N₂O emission fluxes and the soil moisture or soil temperature in Control and NF in 2016 from FI (a) and SI (b), in 2017 from FI (c) and SI (d). (SI-NF and FI-NF refer to the treatment of fertilization from sprinkling irrigation and furrow irrigation. SI-Control and FI-Control refer to the treatment of no fertilization from sprinkling irrigation and furrow irrigation. Vertical bars indicate standard errors. The y-axes in the graphs (a)–(d) are on different scales)

The variables of soil moisture and temperature exhibited generally consistent trends with N₂O emission fluxes from two irrigation systems. The soil moisture and temperature were higher, and N₂O emission fluxes of soils of two irrigation systems were higher in July and August than in May–June and in September (*Fig. 3*). During the irrigation period (from May to September), mean moisture of soil remained 45.9 and 44.5% under the furrow irrigation fertilization (NF) and furrow irrigation control (Control) system, and 39.7 and 34.3% under the sprinkling irrigation fertilization (NF) and sprinkling irrigation control (Control) system in 2016. The mean moisture of soil remained 26.1 and 26.6% under the NF and Control system from FI, and 24.6 and 23.3% under the NF and Control system from SI in 2017 (*Fig. 3*). Mean moisture was generally higher in NF and Control of FI than NF and Control plots of SI. There was no significant effect of two irrigation systems on the average daily soil temperature in the 0–30 cm soil layer from May to September ($p > 0.05$). There was no significant difference in soil temperature and moisture content for fertilized soil and soil without fertilizer of each irrigation system ($p > 0.05$).

Cumulative N₂O emissions in both irrigation systems

A significant difference in cumulative N₂O emissions of soils from the two irrigation systems was measured during the potato growing season in 2016 ($F = 13.84$, $p < 0.001$) and 2017 ($F = 6.49$, $p < 0.001$). The soils in Control of SI ($F = 47.0$, $p < 0.001$), NF of SI ($F = 7.8$, $p < 0.01$), Control of FI ($F = 57.5$, $p < 0.001$), and NF of FI ($F = 3.0$, $p < 0.05$) showed significant differences in the inter-annual cumulative N₂O emissions (*Fig. 4*). The cumulative N₂O emissions were significantly higher for NF and Control from FI than for NF and Control from SI over the annual sunflower growing season. The cumulative N₂O emissions in the fertilized soil were higher than that of the controlled soils each irrigation system. The cumulative N₂O emissions were 373.03 and 425.12 mg/m² for the FI with NF in 2016 and 2017. The cumulative N₂O emissions were 150.40 and 252.01 mg/m² for SI with NF from 2016 to 2017, respectively. The cumulative N₂O emissions from SI with NF were 59.68% and 40.72% lower than those from FI with NF for 2016 and 2017, respectively. The cumulative N₂O emissions of the Control soil from SI were 74.51 and 177.05 mg/m², and were 2.12% (2016) and 2.10% (2017) lower than that of the Control soil from FI in May – September during the annual potato field tested stage (*Fig. 4*). The cumulative N₂O emissions varied significantly with different irrigation systems throughout the potato experimental period. Sprinkling irrigation significantly reduced N₂O emissions.

Emission factor of N₂O

Emission factor of N₂O (EF) denotes the percentage of nitrogen lost in the form of N₂O gas in nitrogenous fertilizer, and can better evaluate the N₂O emission ratio of the fertilizers applied. EF of nitrogen fertilizer has been widely used in estimating regional and global N₂O emission inventories from farmland. The EF increased with N₂O emission due to increasing nitrogen fertilizer applied per unit area. EF from furrow irrigation and sprinkling irrigation in our study was 0.76% and 0.20% in 2016, 0.62% and 0.19% in 2017, respectively (*Fig. 5*). Compared with furrow irrigation, sprinkling irrigation can significantly reduce EF. The EF from sprinkling irrigation was 73.68% and 69.35% lower than that of furrow irrigation in 2016 and 2017. There was no significant difference in the inter-annual EF in furrow irrigation or sprinkling irrigation compared to soil air.

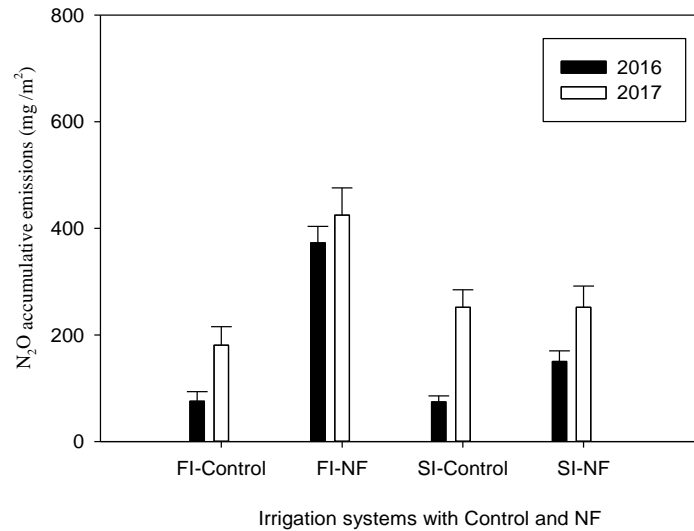


Figure 4. Cumulative N_2O emissions varied significantly in Control and NF with FI and SI throughout the potato experimental period. (SI-NF and FI-NF refer to the treatment of fertilization from sprinkling irrigation and furrow irrigation. SI-Control and FI-Control refer to the treatment of no fertilization from sprinkling irrigation and furrow irrigation. Vertical bars indicate standard errors for each irrigation system)

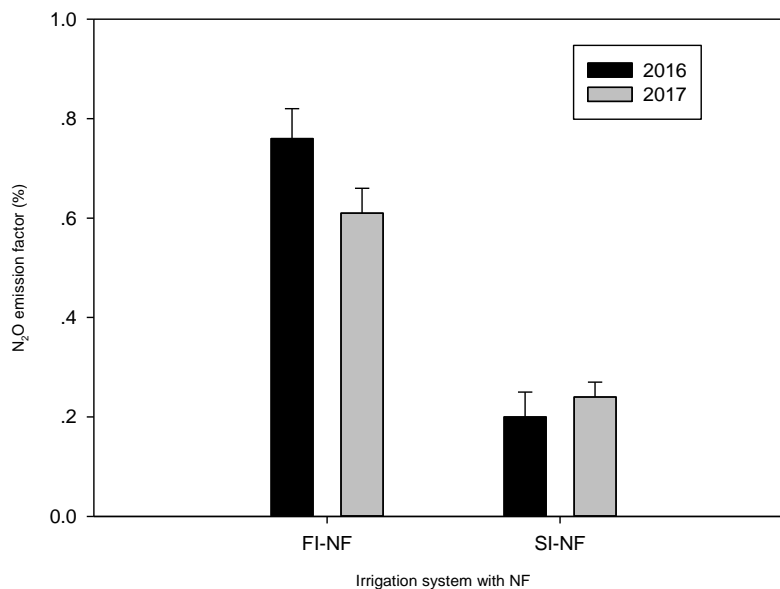


Figure 5. Emission factor of N_2O varied between FI-NF and SI-NF in 2016 and 2017. (SI-NF and FI-NF refer to the treatment of fertilization from sprinkling irrigation and furrow irrigation. Vertical bars indicate standard errors for each irrigation system)

Discussion

Seasonal variation of N_2O emissions in two irrigation systems

The biggest N_2O emission pulses were generated and there are higher emission rate in July and August during the season of vigorous potato growth from 2016 to 2017, in both the sprinkling irrigation and furrow irrigation treatments. Seasonal dynamics of

N₂O emissions fluxes were consistent with the changes of moisture and temperature in soil that were greater in July – August than in May–June and September–October (*Fig. 3*). These discoveries are consistent with the results of Kallenbach et al. (2010) in the soils from other arid and semiarid areas (Kallenbach et al., 2010). The production and consumption of N₂O from the soils are affected via the processes of nitrification and denitrification with microorganisms participating. These processes are all related to soil temperature and moisture (Firestone and Davidson, 1989). Soil moisture controls the biotic and abiotic processes, and operates a critical regulation function in the microbial activities of soils, for instance, N mineralization, nitrification and denitrification that are all quantitatively influenced by the applied irrigation methods (Sánchez-Martín et al., 2008). Climate and soil abiotic factors: soil temperature and moisture, can affect the dynamic changes of N₂O, with visible seasonal characteristics, in particular, in water transport.

N₂O emissions fluxes in the fertilized and control soils from sprinkling irrigation and furrow irrigation

Mean emissions fluxes of N₂O was 152.02 µg/(m² hr) in furrow irrigation, 36.53 µg/(m² hr) in sprinkling irrigation for fertilization treatment from 2016 to 2017. Change of irrigation mode affects N₂O source emission from farmland soil. In furrow irrigation, the peak value of N₂O emissions in the NF was four times higher than in sprinkling irrigation. Sprinkling irrigation compared with traditional furrow irrigation, significantly reduced N₂O emission from potato fields (*Fig. 4*). The amount of applied water in furrow irrigation was more significant than the saturated hydraulic conductivity in the soils, with furrows remaining flooded for several hours. The NH₄⁺-N from the NF in the wetting soils was fleetly nitrified, increasing the concentration of NO₃⁻-N. In FI, the high rate of used water quickly dissolved these fertilizers and produced a great deal of NH₄⁺-N and NO₃⁻-N on the surface layer of the soil profile. Rapidly dissolving a lot of fertilizer would partly illustrate the significantly greater ($P < 0.05$) NO₃⁻-N and NH₄⁺-N concentration found in furrow irrigation system than in sprinkling irrigation system (*Table 1*). The essential differences between the concentration of NO₃⁻-N and NH₄⁺-N of the soil have emerged in the decision on irrigation strategy. The process of soil nitrogen conversion is different from that of N₂O emission between sprinkling irrigation and furrow irrigation. Tensiometers controlled the sprinkling irrigation. The irrigation was triggered when SMP at 0.2 m depth directly under the sprinkling emitters reached – 24.5 kPa. The irrigation was stopped when the amount of water applied to each irrigation event was about 10 mm. Values for the soil NO₃⁻-N and NH₄⁺-N concentration in the upper 10 cm layer for the same fertilizer treatment generally remained lower on NF from SI than FI (*Table 1*). The NO₃⁻-N and NH₄⁺-N that will not be leached were concentrated in the root zone of potato under sprinkling irrigation. The NO₃⁻-N and NH₄⁺-N are beneficial to the uptake of potato due to the low amount of water from sprinkling irrigation. The results of Wang et al.'s (2012) research are consistent with our study (Wang et al., 2012). The concentration of NO₃⁻-N and NH₄⁺-N in furrow irrigation soil is significantly higher than that in water-saving irrigation soil. Sprinkling irrigation reduces the concentration of NO₃⁻-N and NH₄⁺-N, inhibits denitrification and reduces N₂O emissions. High concentrations of NO₃⁻-N and NH₄⁺-N trigger higher N₂O emissions during nitrification and denitrification (Sánchez-Martín et al., 2008). In our study, high NO₃⁻-N and NH₄⁺-N contents in furrow irrigation resulted in high N₂O emission.

Table 1. Basic physical and chemical properties of soil from sprinkling irrigation and furrow irrigation

Year	Treatments	Bulk density (g cm ⁻³)	Porosity (%)	NH ₄ ⁺ -N (mg kg ⁻¹)	NO ₃ ⁻ -N (mg kg ⁻¹)
2016	FI-NF	1.34 ± 0.07a	48.13 ± 1.40a	7.09 ± 1.10a	34.28 ± 1.25a
	SI-NF	1.21 ± 0.03b	49.86 ± 0.53b	6.46 ± 1.00b	22.98 ± 1.60b
	FI-Control	1.35 ± 0.05a	49.23 ± 0.62c	6.64 ± 1.22c	21.76 ± 1.21c
	SI-Control	1.19 ± 0.01b	52.58 ± 0.75d	6.08 ± 1.43d	16.64 ± 1.36e
2017	FI-NF	1.29 ± 0.02c	50.42 ± 2.30e	6.95 ± 1.35e	73.66 ± 2.21f
	SI-NF	1.17 ± 0.02b	55.15 ± 1.80f	6.25 ± 1.06f	37.76 ± 1.13g
	FI-Control	1.29 ± 0.01c	50.09 ± 1.20c	6.76 ± 1.40b	34.41 ± 2.05h
	SI-Control	1.21 ± 0.01b	53.17 ± 0.38d	6.21 ± 1.20d	30.47 ± 1.97i

SI-NF and FI-NF refer to the treatment of fertilization from sprinkling irrigation and furrow irrigation. SI-Control and FI-Control refer to the treatment of no fertilization from sprinkling irrigation and furrow irrigation. NH₄⁺-N and NO₃⁻-N are seasonal mean. Bulk density and porosity are the value at the end of the growing season

Comparing sprinkling irrigation with furrow irrigation in potato field, soil bulk density under sprinkling irrigation (1.17 g/cm³) is lower than that under furrow irrigation (1.29 g/cm³) from 2016 to 2017 (Table 1). Sprinkling irrigation compared with furrow irrigation increases soil porosity, improves soil permeability. The topsoil in sprinkling irrigation fields was looser than that in furrow irrigation fields (Sun et al., 2008). Sprinkling irrigation is one of the water-saving irrigation methods widely adopted in agricultural production. The environmental conditions of soils in sprinkling irrigation were similar to that of drip irrigation (Lv et al., 2010), and favored nitrification, contributing to lower emissions of N oxides (Sánchez-Martín et al., 2008). Both the high consumption and frequency of used water in the furrow irrigation strategy produced the high moisture of soil in the plots. The high moisture in the soils resulted in the emergence of a high proportion of anaerobic environment. High soil moisture not only stimulates soil microbial activity, but also reduces the flow of oxygen in soil, leading to nitrification and denitrification. Use of furrow irrigation gave higher N₂O emission losses than drip irrigation (Sánchez-Martín et al., 2008). Different infiltration and redistribution patterns of irrigation water result in different distribution patterns of soil water in time, horizon and vertical depth, which have an important impact on the production and emission of N₂O and its spatial and temporal distribution. Under drip irrigation, as water supply is low, the process of soil N₂O production from denitrification will be limited, and the N₂O emission will be reduced (Kallenbach et al., 2010; Sánchez-Martín et al., 2010). Soil in furrow-irrigated potato fields emits more N₂O than that in sprinkling-irrigated. Sprinkling irrigation can reduce N₂O emission from farmland soil.

The used NF treatment in the potato field also had a significant impact on the results achieved. The concentration of NH₄⁺-N and NO₃⁻-N was significantly (P < 0.05) greater in the fertilization treatment than in the Control for sprinkling irrigation and furrow irrigation, respectively (Table 1). The N₂O emissions of soils were commonly higher in the fertilization treatment than in the Control in sprinkling irrigation and furrow irrigation throughout the testing stage (Fig. 3). In irrigated agriculture, both the availability of water and N fertilizers has an essential effect on N₂O emissions. Higher concentrations of NH₄⁺ and NO₃⁻ were detected in the soils of NF compared with the

soil of no fertilizer (Vallejo et al., 2005). The effect of the ions from nitrification and denitrification processes caused higher N₂O emissions in the soils with chemical fertilizer compared with the soils of no fertilizer in drip irrigation and furrow irrigation systems (Sánchez-Martín et al., 2008).

Emission factor of N₂O in two irrigation systems

In our study, mean emission factor of N₂O from nitrogenous fertilizer for two-year growth period in potato fields is 0.20 and 0.69 % in sprinkling irrigation and furrow irrigation, respectively. Statistics such as Xu et al. (2016) show that the N₂O emission factor of nitrogen fertilizer is 0.50%~0.82% during the growth period of summer maize, 0.61%~1.13% in a vegetable field in the arid area (Xu et al., 2016). The EF of N₂O from the potato field of furrow irrigation in our study is in the range of EF from Xu et al. (2016) in the upland field. The EF of N₂O in potato field from sprinkling irrigation was significantly lower than that in the soils of the upland field, and it was 61% lower than the lowest EF (0.61%) of N₂O in vegetable soil and 81% lower than the highest EF (1.13%) of N₂O. Sprinkling irrigation significantly reduces N₂O emissions.

Kang and Eltahir (2018) use the Massachusetts Institute of Technology (MIT) Regional Climate Model (MRCM) to perform simulations for the historical period (1975–2005), as well as future climate (2070–2100) assuming two scenarios of GHG emissions with furrow irrigation which cools surface temperature and moistens surface air, but boosts integrated measures of temperature and humidity, and hence enhances intensity of heatwaves. China is currently one of the largest contributors to the emissions of greenhouse gases, with potentially serious implications to its population (Kang and Eltahir, 2018). Sprinkling irrigation in China is widely used to reduce these greenhouse gas emissions.

The irrigation strategy had an important impact on the pattern of N₂O emissions. The choice of an irrigation system is regarded as a critical way of saving water in arid and semiarid regions and maintaining optimal crop yield. In this experiment, sprinkling irrigation has been demonstrated that it can also be used as a tool for mitigating emissions of N₂O. To date, no results have been published comparing sprinkling and furrow irrigation. Although our results indicate that the N₂O emission pattern of sprinkling irrigation contributed to lower emissions on N₂O, many studies will be essential to assess the effect of some parameters related to sprinkling irrigation. These parameters include soil characteristics, especially hydraulic conductivity of affecting water distribution. Moreover, as sprinkling irrigation is frequently combined with applied chemical fertilizer, further work is needed to assess the influence of frequency, rate and type of N fertilized on N₂O emissions via sprinkling irrigation.

Conclusions

This study demonstrated that the choice of irrigation strategy had a significant effect on N₂O emissions. Sprinkling irrigation saves water and also helps to reduce the production of N₂O. Therefore, it can be regarded as an effective method for mitigating the gas loss in the soils of agroecosystems in arid and semiarid areas. Nevertheless, more field studies are needed to assess the influence of the new irrigation technologies on N₂O emissions and the comprehensive influence of using both water and N.

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REFERENCES

- [1] Adviento-Borbe, M. A. A., Linqvist, B. (2016): Assessing fertilizer N placement on CH₄ and N₂O emissions in irrigated rice systems. – *Geoderma* 266: 40-45.
- [2] Aulakh, M. S., Khera, T. S., Doran, J. W. (2000): Yields and nitrogen dynamics in a rice–wheat system using green manure and inorganic fertilizer. – *Soil Science Society America Journal* 64: 1867-1876.
- [3] Auxiliadora, C., Juan, H., Jesús, A. B., Glen, R. (2018): Sensor-based assessment of soil salinity during the first years of transition from flood to sprinkler irrigation. – *Sensors* 18: 1-18.
- [4] Davidson, E. A. (1991): Fluxes of Nitrous Oxide and Nitric Oxide from Terrestrial Ecosystems. – In: Rogers, J. E., Whitman, W. B. (eds.) *Microbial Production and Consumption of Greenhouse Gases: Methane, Nitrous Oxides and Halomethanes*. American Society for Microbiology, Washington, pp. 219-235.
- [5] Diego, A., Alberto, S. C., Gemma, A., Antonio, V. (2017): Rainfall amount and distribution regulate DMPP effects on nitrous oxide emissions under semiarid Mediterranean conditions. – *Agriculture Ecosystems & Environment* 238: 36-45.
- [6] Ezequiel, S., Antonio, P. D. C., Tarlei, A. B., José, A. F., Richard, K., Bruno, M. (2018): Test methods for characterising the water distribution from irrigation sprinklers: Design, evaluation and uncertainty analysis of an automated system. – *Biosystems Engineering* 169: 42-56.
- [7] Firestone, M. K., Davidson, E. A. (1989): Microbial Basin of NO and N₂O Production and Consumption in Soil. – In: Andreae, M. O., Schimel, D. S. (eds.) *Exchange of Trace Gases between Terrestrial Ecosystem and the Atmosphere*. Wiley, London, pp. 7-21.
- [8] Granli, T., Bockman, O. C. (1994): Nitrogen oxide from agriculture. – *Norwegian Journal of Agricultural Sciences* 12: 7-127.
- [9] IPCC (2013): *Climate Change 2013: The Physical Science Basis*. – In: Stocker, T. F., Qin, D., Plattner, G. K., Tignor, M., Allen, S. K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P. M. (eds.) *Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, New York.
- [10] Jiao, Y., Hou, J. H., Zhao, J. H., Yang, W. Z. (2015): Cropland age from grassland conversion to cropland affects nitrous oxide emission. – *Acta Agriculturae Scandinavica, Section B -Soil & Plant Science* 65: 566-574.
- [11] José, C., Eva, T. M., Francisco, M. (2018): Sprinkler irrigation frequency affects maize yield depending on irrigation time. – *Agronomy Journal* 110: 1862-1873.
- [12] Kallenbach, C. M., Rolston, D. E., Horwath, W. R. (2010): Cover cropping affects soil N₂O and CO₂ emissions differently depending on type of irrigation. – *Agriculture Ecosystems & Environment* 137: 251-260.
- [13] Kang, S. C., Eltahir, E. A. B. (2018): North China Plain threatened by deadly heatwaves due to climate change and irrigation. – *Nature Communications* 9: 2894.
- [14] Laura, S. M., Augusto, A., Alejandro, B., Lourdes, G. T., Antonio, V. (2008): Influence of drip and furrow irrigation systems on nitrogen oxide emissions from a horticultural crop. – *Soil Biology & Biochemistry* 40: 1698-1706.
- [15] Li, J., Zhang, J., Ren, L. (2003): Water and nitrogen distribution as affected by fertigation of ammonium nitrate from a point source. – *Irrigation Science* 22: 19-30.

- [16] Lim, S. S., Choi, W. J. (2014): Changes in microbial biomass, CH₄ and CO₂ emissions, and soil carbon content by fly ash co-applied with organic inputs with contrasting substrate quality under changing water regimes. – *Soil Biology & Biochemistry* 68: 494-502.
- [17] Lorenzo, D. M., Martina, M., Alex, C. B., Tiago, A. K., Cleber, M. A. (2018): Classification of rice grains of lowland cultivars grown under flood irrigation and sprinkler irrigation. – *Engenharia Agrícola* 38: 599-605.
- [18] Lv, G. H., Kang, Y. H., Li, L., Wan, S. Q. (2010): Effect of irrigation methods on root development and profile soil water uptake in winter wheat. – *Irrigation Science* 28: 387-398.
- [19] Naghedifar, S. M., Ziaei, A. N., Ansari, H. (2018): Simulation of irrigation return flow from a Triticale farm under sprinkler and furrow irrigation systems using experimental data: A case study in arid region. – *Agricultural Water Management* 210: 185-197.
- [20] Robertson, G. P., Paul, E. A., Harwood, R. R. (2000): Greenhouse gases in intensive agriculture: Contributions of individual gases to the radiative forcing of the atmosphere. – *Science* 289: 1922-1925.
- [21] Sánchez-Martín, L., Vallejo, A., Dick, J., Skiba, U. M. (2008): The influence of soluble carbon and fertilizer nitrogen on nitric oxide and nitrous oxide emissions from two contrasting agricultural soils. – *Soil Biology & Biochemistry* 40: 142-151.
- [22] Sánchez-Martín, L., Mejjide, A., Garcia-Torres, L., Vallejo, A. (2010): Combination of drip irrigation and organic fertilizer for mitigating emissions of nitrogen oxides in semiarid climate. – *Agriculture Ecosystems & Environment* 137: 99-107.
- [23] Schilt, A., Brook, E. J., Bauska, T. K., Baggenstos, D., Fischer, H., Joos, F., Petrenko, V. V., Schaefer, H., Schmitt, J., Severinghaus, J. P., Spahni, R., Stocker, T. F. (2014): Isotopic constraints on marine and terrestrial N₂O emissions during the last deglaciation. – *Nature* 516: 234-237.
- [24] Soil Survey Staff. (1992): *Keys to Soil Taxonomy*. Sixth Ed. – USDA, Washington DC.
- [25] Sun, Z. Q., Kang, Y. H., Jiang, S. F. (2008): Effects of water application intensity, drop size and water application amount on the characteristics of topsoil pores under sprinkler irrigation. – *Agricultural Water Management* 95: 869-876.
- [26] US-EPA (2006): *Global Anthropogenic Non-CO₂ Greenhouse Gas Emissions, 1990-2020*. – United States Environmental Protection Agency, EPA 430-R-06-003, June 2006, Washington DC, USA. Accessed 26 March 2007.
- [27] Vázquez, N., Pardo, A., Suso, M. L., Quemada, M. (2005): A methodology for measuring drainage and nitrate leaching in unevenly irrigated vegetable crops. – *Plant and Soil* 269: 297-308.
- [28] Vallejo, A., Garcia-Torres, L., Diez, J. A., Arce, A., Lopez-Fernandez, S. (2005): Comparison of N losses (NO₃, N₂O, NO) from surface applied, injected or amended (DCD) pig slurry of an irrigated soil in a Mediterranean climate. – *Plant and Soil* 272: 313-325.
- [29] Wang, X. J., Wei, C. Z., Zhang, J., Dong, P., Wang, J., Zhu, Q. C., Wang, J. X. (2012): Effects of irrigation mode and N application rate on cotton field fertilizer N use efficiency and N losses. – *Chinese Journal of Applied Ecology* 23: 2751-2758.
- [30] Xu, Y. X., Guo, L. P., Xie, L. Y., Yun, A. P., Li, Y. C., Zhang, X., Zhao, X., Diao, T. T. (2016): Characteristics of background emissions and emission factors of N₂O from major upland fields in China. – *Scientia Agricultura Sinica* 49: 1729-1743.
- [31] Yang, W. Z., Yang, M. D., Wen, H. Y., Jiao, Y. (2018): Global Warming Potential of CH₄ uptake and N₂O emissions in saline-alkaline soils. – *Atmospheric Environment* 191: 172-180.
- [32] Zapata, N., Robles, O., Playán, E., Paniagua, P., Romano, C., Salvadorb, R., Montoya, F. (2018): Low-pressure sprinkler irrigation in maize: differences in water distribution above and below the crop canopy. – *Agricultural Water Management* 203: 353-365.