Partial wetting irrigation resulted in non-uniformly low nitrous oxide emissions from soil

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ABSTRACT

Partial wetting irrigation influences soil moisture distribution, which potentially changes soil nitrous oxide (N₂O) emission. **Incubation** experiments were conducted to reveal the impact of non-uniform moisture distribution on soil N₂O emissions under subsurface-drip-irrigation (SDI), with surface-irrigation (SI) as a control. Results indicated that soil N₂O emission from different subregions of SDI soil varied synchronized to soil moisture. The wetting-drying process in different soil subregions under SDI incurred pulse N₂O emissions unexceptionally, but the pulse magnitudes and timing of the occurrence varied among subregions. The pulse **N₂O emission magnitudes** positively correlated **to the match degree of soil moisture to the optimal soil moisture level for peak N₂O emissions**. The soil water-filled-porosity WFPS ranges for peak N₂O fluxes, **the determine coefficient of the exponential functions between N₂O flux and soil WFPS and its average slopes**, decreased gradually from the central to periphery SDI soil subregions. Both peak and cumulative N₂O fluxes were much lower from the periphery subregions than from central subregions. On the whole, SDI reduced the cumulative N₂O emissions by 77.3–86.7% **compared to SI**, with periphery subregions of R3 and R4 contributing for more than 76%. The partial wetting SDI irrigation can significantly reduce soil N₂O emissions and is a promising strategy for soil N₂O emission mitigation. Further research should be conducted on how to design SDI properly to balance the soil moisture uniformity/efficiency and soil N₂O emission reduction.

Keywords: Partial wetting irrigation; Non-uniformly distribution; N₂O emission; Subsurface drip irrigation

1. Introduction

Nitrous oxide (N₂O) is one of the most important greenhouse gases (GHGs), **with a global warming potential (GWP) 298 times that of** carbon dioxide (CO₂) on a 100-year scale (Pachauri et al., 2007; IPCC, 2013; Hou et al., 2016). N₂O is as well a key compound being involved in the destruction of stratosphere ozone (Ravishankara et al., 2009; Repo et al., 2009; Arévalo-Martínez et al., 2015). The atmospheric N₂O concentration was 324 ppb in 2011, about 20% higher than the pre-industrial levels (IPCC, 2013). According to **the IPCC fifth assessment report**, agricultural ecosystems account for 59.4% of the global anthropogenic N₂O emission, while soils under natural vegetation account for 60% of natural source N₂O emissions (IPCC, 2013). Studies on N₂O emissions either from agricultural soil or from natural vegetated soil are of global significance for mitigation of global **greenhouse gas**

emission and climate change (Reay et al., 2012; Schaufler et al., 2010).

Soil N₂O emissions are influenced by various environmental factors, such as temperature, moisture, nitrogen fertilization, land use, and soil pH (Smith et al., 2003; Schaufler et al., 2010; Hofstra, et al., 2005; Rochette et al., 2008; Regina et al., 2010; Yamamoto et al., 2012). Soil moisture has been recognized as an important factor in triggering N₂O emissions (Hou et al., 2016; Hadi et al., 2010; Jauhiainen et al., 2012; Weitz et al., 2002) by influencing the gas diffusivity (Smith et al., 2003), soil redox status (Xing et al., 2002) and the activity of nitrifiers and denitrifiers (Amha et al., 2003; Ruser et al., 2006; Scheer et al., 2008).

The impact of soil moisture on N₂O emissions has been intensively investigated in recent years. Previous researchers revealed the impacts of irrigation method or moisture contents on soil N₂O emissions (Hou et al., 2012; Nosalewicz et al., 2013; Vargas et al., 2014) and found that peaks of N₂O production was highly sensitive to water management, and the pulse N₂O emissions were generally enhanced for several days following precipitation or irrigation (Khalil and Baggs, 2005; Koga, et al., 2004; Kusa et al., 2006; Kallenbach, et al., 2010; Deng et al., 2012; Sanger et al., 2010). Generally, substantial N₂O fluxes occurred when water-filled-porosity (WFPS) was in the range of 45%–90% (Hou et al., 2012; Dobbie et al, 1999; Xu et al., 2013), and large amounts of N₂O were emitted during the wetting-drying process (Hou et al., 2012; Nagata et al., 2010; Peng et al., 2011; Zhang et al., 2012). For example, Vargas et al. (2014) investigated N₂O emissions from packed soil columns under four soil moisture levels, and indicated that the effects of crop residue on greenhouse gas emissions were exacerbated in periods with high soil moisture. Koga et al. (2004) observed the peak N₂O flux of 942.9 $\mu\text{g N}_2\text{O m}^{-2} \text{ h}^{-1}$ from Andisols in Eastern Hokkaido immediately after a heavy rainfall. Zhang et al. (2012) found that rainfall or irrigation typically enhanced soil N₂O peak emissions from wheat-green onion rotation system. Yao et al. (2010) and Hou et al. (2016) suggested that peak N₂O emissions occurred during repeated drying-wetting cycles from rice-wheat rotation system. Although there has been adequate information about the effects of moisture condition on soil N₂O emissions, most of those studies examined the N₂O emissions from soils with moisture distributed uniformly at horizontal direction (or ignored the influence of non-uniform soil moisture distribution) (Scheer et al., 2008; Du, et al., 2006). Only a few literatures (Sanchez-Martın et al., 2008, 2010; Kennedy et al., 2013) found partial soil wetting under drip irrigation resulted in low N₂O emissions compared to surface irrigation. But they measured N₂O emissions from soil around the emitter as a whole (Sanchez-Martın et al., 2008,

2010; Kennedy et al., 2013), and did not quantify the different in N₂O emissions among different subregions around the emitter along the distance to emitter in horizontal direction.

With the development of modern irrigation techniques, soil is characterized as 'partial wetting' after point source irrigation applied by techniques such as subsurface-drip-irrigation (SDI), drip irrigation, or seepage irrigation. Under partial wetting condition, the soil moisture will distributed non-uniformly both in horizontal and vertical directions (Kallenbach et al., 2010; Wang et al., 2016). That will definitely result in changes in both the magnitude and spatial distribution of soil N₂O emissions. Recently, few papers reported N₂O emissions from soil under drip irrigation or subsurface-drip-irrigation (Sánchez-Martín et al., 2008, 2010; Kennedy et al., 2013). For instance, Sánchez-Martín et al. (2008) indicated that drip irrigation resulted in less N₂O emissions than furrow irrigation from a horticultural soil. Wang et al. (2016) examined the effects of different irrigation method on GHGs emissions in winter wheat field in the North China plain, and indicated that surface drip irrigation might not only guarantee yield stability, but also reduce N₂O emissions by 14.9% than flood irrigation. Kennedy et al. (2010) suggested that SDI irrigation practice which interrupted the environment that favored the denitrification, was a promising strategy for mitigating soil N₂O emission. However, if the N₂O emissions are different among soil subregions around the drip emitter with different moisture conditions under partial wetting irrigation, and if the impact of soil moisture contents on N₂O emissions is different among the subregions are still not clear.

Subsurface-drip-irrigation (SDI) as one of the widely applied partial wetting irrigation practices, frequently resulted in non-uniform soil moisture distribution (Scheer et al., 2008; Kallenbach et al., 2010). That consequently led to remarkable change in soil aeration, the transform of soil nitrogen, the distribution of soil NH₄⁺ and NO₃⁻, and soil microorganism properties (Kouznetsov, et al., 2004; Badr et al., 2013), which could largely influence the production and emission of N₂O, especially during the watering-drying process. Assuming that soil moisture distribution (either vertical or horizontal) characteristics have a great impact on N₂O emissions, the objectives of this study are 1) to measure N₂O fluxes from a horticultural soil under two different irrigation regimes (surface-irrigation, SI and subsurface-drip-irrigation, SDI) in an incubation experiment; 2) to qualify the N₂O emissions from different subregions around the emitter along the distance to emitter in horizontal direction and testify that if the SDI is helpful to mitigate soil N₂O emission; and 3) to reveal the difference in the relationships between soil moisture variation and soil N₂O emissions among different subregions in

SDI soil.

2. Methods

2.1 Experimental design

To investigate the impacts of the non-uniform soil moisture distribution patterns under SDI on soil N₂O emissions, incubation experiments were conducted on silty clay soil from August to December 2014 in Nanjing (32° 03' N, 118° 46' E), Jiangsu Province, China. Detailed information about the soil can be found in Xu et al. (2016). Two irrigation regimes with three replications, namely SI and SDI, were applied to the soil to reveal the influence of different moisture distribution characteristics on N₂O emission from horticultural soil. The soil was air-dried, ground using a hammer mill, sieved, homogenized and packed into soil mesocosms (the soil boxes were 40 cm × 40 cm × 60 cm and 80 cm × 40 cm × 60 cm for SI and SDI treatments, respectively) at the bulk density of 1.25 g cm⁻³ for the surface 0–10 cm depths and 1.33 g cm⁻³ for the 10–50 cm depths. The soil was packed into the boxes four months before the beginning of the experiments, and kept undisturbed to avoid the influence of soil disturbance on soil N₂O emission. For the SI treatment, water was applied to the soil surface to replenish the soil moisture to field capacity at 0–20 cm depth. For the SDI treatment, water was supplied from the subsurface drip emitter (at 30cm depths in the mid-line location at one side of the box, Fig.1) connected to a Marriott bottle to form a specific soil partial wetting pattern that only a little part of surface soil was wet (as illustrated in the Results section). For the SI and SDI treatments, water were applied at 10:00 h on 24 August in volumes of 7500 and 2500 mL for the first watering, and at 10:00 h on 9 October in volumes of 7000 and 2200 mL for the second watering.

2.2 Soil moisture measurement

For the SI treatment, soil samples of about 2–3g for every 4 cm soil layers from top 0 to 24 cm soils were collected at 10:00 h through holes of 20 mm diameter in the soil box using stainless samplers (18 mm diameter). For the SDI treatment, soil samples were collected in two dimensional directions through 10 mm holes in the soil box using an 8 mm stainless sampler, at 5cm intervals from 0 to 55 cm depths vertically and from 2.5 to 37.5 cm horizontally. The soil samples were taken daily during the first five days and then 3 or 5 days once until the second watering. To minimize the disturbance of soil sampling, the soil with the approximately same moisture content were refilled the box through the holes after the first five sampling or every two or three samplings for later sampling. Soil moisture content in soil samples were determined by oven drying weighted method. Water-filled pore space

(WFPS) was calculated as the percentage of soil volumetric moisture content to the soil porosity (Beare et al., 2009; Ding et al., 2007), with the soil porosity of 52.8% and 49.8% in 0-10cm and 10-50cm depths, respectively.

2.3 N₂O fluxes measurement

On each sampling day, the gas samples were collected from four different half circle ring subregions (R1, R2, R3 and R4, 1–9cm, 10–18cm, 19–27cm and 28–36cm from the emitter horizontally) in each SDI soil box using the static chamber method at 10-minute intervals between 9:45 h and 10:15 h (Hou et al., 2016; Peng et al., 2011). At the same time, gas samples were collected from the SI soil box by a cubic (40 cm × 40 cm × 40 cm) static chamber with one compartment (as described by Sánchez-Martín et al., 2008, 2010). The chambers were made of polyvinyl chloride and equipped with thermometers and electric fans at the top for measuring air temperature and mixing air inside during the sampling period. The chamber was wrapped with a layer of heat insulation material to minimize the impact of heat transfer caused by air temperature. The bases for the chambers were inserted in soil for 0–5 cm depth when the soil boxes were refilled, and remained there until the end of study. Detailed information about the SDI chamber and the base is illustrated in Fig. 1.

N₂O concentrations in the gas samples were analyzed by an Agilent 7890A gas chromatograph system equipped with an electron capture detector (ECD). Fluxes of N₂O were calculated according to the linear increase rate of N₂O concentration and the temperatures inside the chamber (Hou et al., 2012). Average N₂O fluxes from SDI treatment were calculated as the weighted average of fluxes from R1, R2, R3 and R4 subregions with the surface area of each subregion as weight.

2.4 Statistical Analysis

Statistical analysis was performed using the statistical software package SPSS 19.0 (SPSS Inc., Chicago, USA). The paired *t* test was performed to detect the difference in the N₂O fluxes between SI and SDI treatments among different observation periods. The software Surfer 11.0 (Golden Software, USA) was used to map the soil moisture distribution under SDI treatments.

3. Results

3.1 Soil moisture distribution

The soil moisture under different treatments are plotted in Fig.2 and 3. The soil moisture in the top soil layer varied significantly in both treatments, due to the process of infiltration and loss of

evaporation. In SI soil, the soil moisture was higher in top soil layers than in deep soil layers during 0–240 h after both waterings. Soil moisture decreased significantly in top soil layers and increased slightly in deep soils layers, and soil moistures were more variable at depths of 0, 4, 8 and 12 cm than deep soil beneath 12 cm depth (Fig.2). The WFPS in top 0–12 cm soils decreased gradually from 87.0%–91.7% and 82.5%–89.6% to 10.7%–18.5% and 9.4%–16.9% during the period of 24 h–816 h and 24 h–864 h after the first and second watering, respectively.

For the SDI treatment, there is only a little part (about 1.7%) of surface soil was wet at 24h after initial wetting, and the wetting body for soil beneath surface is in ellipsoid shape with drip emitter as center (Fig.3). In SDI soils, the soil moisture distributed non-uniformly at both horizon and vertical directions, and redistributed after initial watering because of the matric potential gradient and evaporation. Soil moisture migrated gradually among different subregions, and the contour lines of the soil moisture distributed in an approximate ball-crown body which were approximately parallel to each other in the vertical profile (Fig.3). Generally, the soil moisture decreased gradually at horizontal direction with an increasing radical distance to the center. At 24 h after the first watering, soil WFPS in each soil column (in 0–30cm depth) at 2.5, 7.5, 12.5, 17.5, 22.5, 27.5, 32.5 and 37.5cm distance from the center were 52.6%, 43.8%, 39.1%, 33.3%, 27.4%, 26.2%, 14.5% and 10.7%. Then soil moisture in different zones decreased along with the time, with the soil WFPS ranges reduced to 8.8%–40.4%, 7.1%–34.4% and 5.9%–21.9% at 240h, 456h and 816h after the first watering. The soil moisture among different soil columns after the second watering showed a similar pattern to that after the first watering, but its moisture contents were slightly higher. The SDI soil resulted in a non-uniform moisture distribution, and consequently led to a variation in soil moisture dynamics among horizontal subregions of SDI soil.

3.2 N_2O fluxes from different subregions of SDI soil

N_2O emission from SI soil was plotted in Fig.4, together with the N_2O fluxes from different subregions of SDI soil (Fig.5). In SI soil, N_2O fluxes were higher than $667.29 \mu g N_2O m^{-2} h^{-1}$ during the first 48 hours after the first watering, when soil WFPS fell within the range of 73.6%–81.2% in 0–12 cm topsoil (Fig.4). Subsequently the N_2O fluxes declined rapidly with the decrease in soil moisture and varied in the range of 22.21 – $310.25 \mu g N_2O m^{-2} h^{-1}$ during the period of 72 h–816 h after initial watering when soil WFPS reduced from 67.6% to 12.2% in 0–12 cm topsoil. The N_2O fluxes after the second watering showed similar patterns to those after the first watering with the maximum flux of

243.14 $\mu\text{g N}_2\text{O m}^{-2} \text{h}^{-1}$ at 24 h after the second watering when the WFPS in 0–12 cm soils ranged from 74.5% to 84.3%. The peak of the short-term pulse N_2O emission after the second watering was 717.6% higher than the flux observed prior to the second watering (at 816 hours after the initial wetting).

In contrast, the N_2O fluxes from different subregions of SDI soil were slightly different from each other among different subregions, and were all significantly lower than those from SI soil (Fig.4 and 5). Generally, the N_2O fluxes from different subregions of SDI soils reduced with the increase of the horizontal distance to the emitter. The N_2O fluxes from R1 subregion in SDI soil were high during the first 48 h ($>79.16 \mu\text{g N}_2\text{O m}^{-2} \text{h}^{-1}$) with a peak of $101.26 \mu\text{g N}_2\text{O m}^{-2} \text{h}^{-1}$ occurred at 48 h after initial wetting when the WFPS (43.7% in 0–20 cm topsoil) fall within the previously reported optimal WFPS range for peak N_2O emissions. Then, the N_2O emissions reduced gradually to $4.97 \mu\text{g N}_2\text{O m}^{-2} \text{h}^{-1}$ (720 h after initial wetting) with the decrease of soil moisture during the period of 48 h–816 h after the first watering. The N_2O emissions from R2, R3 and R4 subregions of SDI soil likely varied in a similar pattern which were slightly different from those in R1, with the peaks appeared 24 h, 72 h, and 192 h later, and the peak values decreased by 24.8%, 33.3%, and 50.5% than in R1 subregion.

The N_2O fluxes from different subregions varied synchronously to the soil moisture (Fig.5). In R1 subregions, the maximum WFPS appeared immediately after the watering event, the peak N_2O occurred almost simultaneously. While in R2, R3 and R4, the maximum WFPS appeared 48-96 hours after initial soil wetting, the peaks of N_2O fluxes occurred 24 h, 48 h and 96 h later than the peak time of WFPS. Similarly, the second watering-drying cycle also induced large amount of N_2O emissions appeared at the beginning after soil wetting, with the peak fluxes mainly ranged from 43.93 to $85.21 \mu\text{g N}_2\text{O m}^{-2} \text{h}^{-1}$ in subregions of R1, R2, R3 and R4, which were 15.8%, 18.8%, 26.7% and 12.4% lower than those after the first watering, respectively. Simultaneously, the peak N_2O fluxes after the second watering appeared 0-48 h later than those after the first watering. And the time gaps between the peak time of N_2O fluxes and the maximum WFPS after the first watering were slightly shorter than those after the second watering. Over the observation period from the first watering to the end of the whole experiment, the N_2O fluxes in all subregions from SDI soil were significantly lower than those from the SI soil ($p < 0.05$ according to pairwise t test, Table 1), with the least fluxes in R4. Moreover, the ranges of soil moisture corresponding to peak N_2O fluxes from SDI soil usually lower than those in SI soil, and those soil moisture ranges decreased with the increase of the horizontal distance to the emitter in SDI soil.

3.3 Reduction in SDI soil N₂O emissions

Generally, N₂O fluxes from SI soil and different subregions of SDI soil after two waterings were in the sequence of SI > R1 > R2 > R3 > R4. N₂O fluxes from all subregions of SDI soil were significantly lower than those from SI. As a whole, the average N₂O fluxes from subregions R1 to R4 of SDI soil were significantly less than those from SI soil after the two waterings, reduced on average by 77.3%–86.7%, respectively (Table 1). Furthermore, fluxes from subregions R3 and R4 were significantly lower than those from subregions R1 after both waterings (Table 1). Meanwhile, the subregions of R3 and R4 accounted for a large proportion (more than 70%) of soil surface area in SDI soil, the total contribution of subregions of R3 and R4 in N₂O reduction rate was as high as 86.4% and 83.8% after both waterings. The differences among subregions were more remarkable during the pulse period after waterings than post-pulse period. The average N₂O fluxes from R3 and R4 of SDI soil were significantly lower than those from R1 during post-pulse emission periods of 0–240 h and 0–360 h after the first and second waterings, respectively. However, no significant difference was observed among N₂O emissions from the different subregions after the peak time (360 h–864 h) after the second watering.

The cumulative N₂O emissions from R1, R2, R3 and R4 subregions of SDI soil were 22.68, 19.83, 15.34 and 12.81 mg m⁻² in 816 hours after the first watering, 20.72, 17.66, 15.03 and 12.78 mg m⁻² in 864 hours after the second watering, with the cumulative fluxes from R4 as the least (Fig. 6). Compared with the SI soil, the cumulative N₂O fluxes from subregions of R1 to R4 of SDI soil were decreased by 76.9%, 80.0%, 83.8% and 86.4%, respectively. The soil surface area weighted average cumulative N₂O flux was summed as 30.36 mg m⁻² after both waterings, reduced by 83.8% than those from SI soil (187.82 mg m⁻²). Generally, the cumulative N₂O fluxes in all subregions or the surface area weighted average N₂O fluxes from SDI soil were all significantly less than those from SI soil ($p < 0.05$). Furthermore, the differences in cumulative N₂O fluxes between every two different subregions of SDI soil were significant at $p < 0.05$ level, except the case between R1 and R2 after the second watering (Fig. 5).

4. Discussion

The N₂O emissions from different subregions of SDI soil varied synchronized with soil moisture in current research (Fig. 5). The wetting-drying process in different subregions of SDI soil incurred pulse N₂O emissions unexceptionally, though the magnitudes and occurrence times of the pulse emissions

were quite different among subregions. Generally, the moisture in SI and subregion of R1 (SDI) soils decreased gradually, whereas in subregions of R2, R3 and R4 (SDI) soil moisture decreased after a short period of increase. The soil moisture in subregions of R3 and R4 varied with a lag in temporal process and in a smaller variation range than R1 and R2. As a result, the magnitude of pulse N₂O emissions was lower in subregions of R3 and R4, and occurrence times were later in subregions of R3 and R4. Furthermore, the peak fluxes usually appeared 24 h-120 h later than corresponding high soil WFPS during the pulse N₂O emissions period, and the time gaps were more evident in subregions of R3 and R4 than in R1 and R2. It indicated that both the magnitude and occurrence time of the pulse N₂O emissions in current research was triggered by the variation in soil moisture (Hou et al., 2012; Metivier et al., 2009).

As stated above, N₂O emissions were triggered by and depended on WFPS. With increasing distance to the drip emitter, soil moisture decreased. For this reason the observed peaks decreased as well (Fig.5). The correlation analysis indicated that the N₂O fluxes in different subregions increased exponentially with the increase in soil WFPS (Table 2). The determine coefficient of the exponential functions between N₂O flux and soil WFPS, as well as its average slopes, decreased gradually from the central to periphery subregions. The coefficient in the periphery R3 and R4 subregions was lower than the overall region, and for central subregions of R1 and R2 it was higher (Table 2). These results suggested that the impact of soil moisture on N₂O emission might be different among different subregions in SDI soil.

Moreover, it has been reported that peak N₂O emissions were measured from soils when the WFPS was in the range of 60%–70% (Bateman and Baggs, 2005; Bouwman et al., 1998), 45%–75% (Hansen et al., 1993), 75%–86% (Hou et al., 2012; Sey et al., 2008), or 45%–60% (Khalil et al., 2005). If the soil moisture is extremely low, nitrification is responsible for N₂O emissions and it will be limited due to the low transfer rate of NH₄⁺, and hence lead to a less emission. If the soil moisture keep at a higher level, denitrification is more active and responsible for peak emissions, but when under completely anaerobic conditions, denitrification to N₂ may dominate and for this reason reduce the emission of N₂O (Skopp et al., 1990). In current research, the high peak N₂O emissions from both SI and SDI soils were measured immediately after the high WFPS, when the soil WFPS in 0–12 cm and 0–20 cm top soil fell within the ranges of 72.7%–85.4% and 31.4%–45.9% after the first waterings, and 75.5%–88.3% and 31.2%–46.9% after the second waterings. The WFPS for peak N₂O emissions in

subregions of R3 and R4 from SDI soil (37.5%-39.0% WFPS and 31.2%- 31.4% WFPS in R3 and R4, respectively) was substantially lower than in the subregions of R1 and R2 (45.90%-46.91% and 42.1%-42.8% WFPS), and lower than the previously reported suitable soil moisture range (45%-75% WFPS) for peak N₂O emission (Khalil et al., 2005; Bateman et al., 2005; Bouwman et al., 1998; Hansen et al., 1993). Regression between maximum soil moisture increment (calculated as difference between maximum WFPS after irrigation and initial WFPS before irrigation, namely $WFPS_M - WFPS_I$) and peak N₂O flux during pulse emission indicated that the peak N₂O fluxes increased exponentially with the increase in soil moisture increment $WFPS_M - WFPS_I$ (Fig.7). The current results are likely suggesting that the soil wetting-drying processes resulted in pulse N₂O emissions, and the magnitude of the pulse N₂O emissions are likely positively correlated to the match degree of soil moisture to the optimal soil moisture level for peak N₂O emissions. It caused short-term pulse N₂O emissions, even if the soil moisture could not increase to the reported level for peak N₂O emissions, although the pulse was lower in its magnitude than those in SI wetting-drying process. It indicated that microorganisms employed in soil N₂O emissions might response to a minor amplitude increase in soil moisture, and maintain a relative high activity at a low WFPS level (Bateman et al., 2005).

Due to different soil water dynamics in different subregions of SDI soil, the N₂O emissions triggered by soil moisture were different among subregions of SDI soil (Fig. 5). As a result, the contributions in reducing N₂O emissions from SDI soil were different among subregions. The cumulative N₂O emissions from different subregions of SDI soil mainly fell within 12.81–22.68 mg m⁻² and 12.78–20.72 mg m⁻² after the two waterings, which were 80.2%–88.8% and 69.6%–80.4% lower than those from SI soil. We can conclude that the partial wetting conditions could effectively reduce the N₂O emissions during one wetting-drying process after a specific irrigation event from bare soil. Moreover, the potential of N₂O emissions reduction in subregions of R3 and R4 from SDI soil was much greater than those in subregions of R1 and R2. Therefore, it can be inferred that SDI irrigation could be effective for mitigating the N₂O emissions possibly because of its special wet body distribution, namely partial wetting after irrigation and with a large portion of subregions R3 and R4 which had high N₂O emission reduction rate. It implied that there might be an ideal or optimal partial wetting pattern, which is not only a promising countermeasure to mitigate the soil N₂O emissions, but also a good guarantee to maintain irrigation uniformity and effectiveness. The ideal partial wetting pattern could be realized by identifying the reasonable irrigation technology parameters (such as the

drip emitter depth and irrigation volume). Furthermore, the transpiration from plant cultivation soil will consume more water than from bare soil. That will result in low soil moisture contents and increment in soil moisture after irrigation. That might be help in reducing the peak flux during pulse emission triggered by soil wetting. Meanwhile, the plant residuals and root exudate can provide organic matters for soil microorganism, and enhance the activity of soil microorganism. Therefore, N₂O fluxes from different soils with plant management must be examined under partial wetting patterns to reveal the influence of moisture distribution patterns on soil N₂O emission, and to figure out the ideal soil-wetting pattern.

It is clear in Fig. 5 that a large part of soil at the end of the incubation was very dry, with the soil moisture much lower than the soil moisture thresholds (assuming 55%-65% of field capacity for upland crops) for irrigation. The N₂O emission during this period was also very low (Fig.5). It means that the N₂O emission reduction rates of 80.2%–88.8% and 69.6%–80.4% calculated based on the cumulative N₂O emissions for the total incubation period were overestimated. Based on the soil moisture, we deduced that the soil moistures in SI and SDI soil at 240 h and 96 h after the first watering and 312 h and 120 h after the second watering were near the soil moisture thresholds for upland crops irrigation. Compared to the N₂O emissions from SI soil in 240 h and 312 h after the first and second watering, the N₂O emissions from different subregions of SDI soil in the same period were reduced by 65.8%–78.2% and 56.7%–64.2% after the two waterings, respectively. Since the time for water depletion to the irrigation threshold was shorter in SDI soil than in SI soil, there should be more frequent irrigation (or wetting-drying) events in SDI fields in a certain period (such as during the growing season for a certain crop). There will be more pulse N₂O emissions events in SDI field than in SI field. That means the reduction percentage of SDI in seasonal cumulative N₂O emission in field application will not as high as reported in current incubation experiment.

Moreover, the water was applied to a very dry soil (WFPS=18.6%-23.5%) in our research, and the N₂O production rate in the dry soil was low (Weitz et al., 2001; Hou et al., 2012). We can infer that the N₂O emission from both SI and SDI soils will be higher than the current results if the initial (before irrigation) soil moisture is more suitable for soil N₂O production. The reduction rates in different subregions of SDI soil should be further investigated under different initial soil moisture levels in future. Furthermore, our conclusion is drawn based on short period incubation experiments without plant cultivation and fertilization. Since plant growth and fertilization management are important

factors linked to soil N₂O emissions (Kallenbach et al., 2010; Mc Taggart et al., 2002), the influence of non-uniform moisture distribution pattern on N₂O emission should also be examined in field experiments under the condition with plant growth and fertilization management in the future. Thus, field experiments should be done with crop cultivation and fertilization management, to investigate whether the SDI is an efficient countmeasure to mitigate soil N₂O emission, and to qualify its effects on mitigating soil N₂O emission and enhancing crop yield.

5. Conclusion

Overall, N₂O emission from different SDI soil subregions with different soil moisture dynamics varied synchronized to soil moisture dynamics. The wetting-drying process in different subregions of SDI soil incurred pulse N₂O emissions unexceptionally, though the magnitudes and occurrence times of the pulse emissions were fairly different among subregions. The peak emissions of N₂O among different subregions from SDI soil appeared orderly with the soil moisture redistribution in the horizontal direction, but the peak fluxes was usually 24 h–120 h behind the corresponding peak WFPS. The magnitude of the pulse N₂O emissions are likely positively correlated to the match degree of soil moisture to the optimal soil moisture level for peak N₂O emissions. The ranges of soil WFPS corresponding to peak N₂O fluxes, the determine coefficient of the exponential functions between N₂O flux and soil WFPS and its average slopes, decreased gradually among different subregions in SDI soil, from the central to periphery subregions. Both peak and cumulative fluxes from the periphery R3 and R4 subregions were much lower compared to those from central subregions of R1 and R2. Over the whole observation period, SDI reduced the cumulative N₂O emissions by 76.9%–86.4% than SI soil, with subregions R3 and R4 contributed for more than 76%. The partial wetting SDI irrigation can significantly reduce soil N₂O emissions and is a promising strategy for soil N₂O emission mitigation. Designing SDI properly by changing the distribution proportion of the periphery R3 and R4 subregions in SDI soil to balance the soil moisture uniformity or efficiency and soil N₂O emission reduction based on field experiments is a promising topic for future research.

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Fig. 1. Sketch of the SDI chamber and the base.

Fig. 2. Soil moisture distributions in SI treatment.

(a) After the first watering (August 25th–September 29th, 2014)

(b) After the second watering (October 9th–November 14th, 2014)

Fig. 3. Soil moisture distributions in SDI treatment.

Fig. 4. N₂O emissions from SI soil after both watering.

(a) After the first watering (August 25th –September 29th, 2014)

(b) After the second watering (October 9th –November 14th, 2014)

Fig. 5. N₂O emissions from different subregions in SDI soil after both watering .

Figure 6. Cumulative N₂O emissions from SDI soil and its reduction rates compared with SI soil (SI and SDI represent surface-irrigation and subsurface-drip-irrigation, respectively; R1-R4 represent different subregions in the horizontal direction of SDI treatment, and the average represent the area weighted average of cumulative fluxes from different subregions; Different letters on each bar represent significant difference in N₂O emissions at $p = 0.05$ level).

Fig. 7. The relation of peak N_2O fluxes and soil moisture increment ($\text{WFPS}_M - \text{WFPS}_I$ represent the difference between maximum WFPS after irrigation and initial WFPS before irrigation).

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Table 1. Average nitrous oxide fluxes ($\pm$ standard error) during different sampling periods

Watering	Observation stage	N ₂ O emission values / $\mu\text{g N}_2\text{O m}^{-2} \text{h}^{-1}$				
		SI	SDI			
			R1 (1-9cm)	R2 (10-18cm)	R3 (19-27cm)	R4 (28-36cm)
The first watering (August 25th, 2014)	0–240 h (n=10)	327.39 $\pm$ 84.88a	55.39 $\pm$ 7.03b	43.72 $\pm$ 5.22bc	34.88 $\pm$ 4.97c	29.37 $\pm$ 4.08c
	240 h–816 h (n=15)	73.31 $\pm$ 9.39a	10.95 $\pm$ 3.53b	19.44 $\pm$ 3.02b	14.14 $\pm$ 2.75c	11.51 $\pm$ 2.24c
	0–816 h (n=25)	174.94 $\pm$ 41.92a	34.12 $\pm$ 4.93b	29.15 $\pm$ 3.63b	22.43 $\pm$ 3.27c	18.66 $\pm$ 2.73c
The second watering (October 9th, 2014)	0–360 h (n=15)	140.80 $\pm$ 12.27a	34.53 $\pm$ 4.22b	30.03 $\pm$ 3.23bc	24.52 $\pm$ 2.44c	21.38 $\pm$ 2.31c
	360 h–864 h (n=10)	52.22 $\pm$ 10.39a	16.05 $\pm$ 1.83b	15.20 $\pm$ 2.40b	13.49 $\pm$ 2.23b	13.07 $\pm$ 2.69b
	0–864 h (n=25)	105.37 $\pm$ 12.14a	27.14 $\pm$ 3.19b	24.10 $\pm$ 2.59bc	20.10 $\pm$ 2.01c	18.06 $\pm$ 1.91c
Both waterings	0–1680 h (n=50)	14016 $\pm$ 22.16a	30.63 $\pm$ 2.95b	26.62 $\pm$ 2.24b	21.27 $\pm$ 1.91c	18.36 $\pm$ 1.65d

537 Note: SI, SDI represents surface-irrigation and subsurface-drip-irrigation, respectively. R1, R2, R3, and R4 represent the subregions of SDI soil. The number following the observation stage
538 indicated sampling days. Different letters in each row represent significant difference in N₂O emissions between different subregions or treatments at $p = 0.05$ level.

Table 2. The relation of soil moisture to N₂O emission for each subregion

Subregion	Relation	Correlation coefficient (R ²)	Significance	Average slope
R1 (1-9cm)	$y=2.639e^{7.221x}$	0.723	p<0.01	216.13
R2 (10-18cm)	$y=3.763e^{6.328x}$	0.557	p<0.01	151.12
R3 (19-27cm)	$y=3.126e^{7.486x}$	0.465	p<0.01	121.44
R4 (28-36cm)	$y=3.107e^{8.563x}$	0.494	p<0.01	104.18
Overall	$y=3.799e^{6.493x}$	0.556	p<0.01	137.25

540 Note: R1, R2, R3, and R4 represent the subregions of SDI soil.