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Matching crop row and dripline distance in subsurface drip irrigation increases yield and mitigates N_2O emissions

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ABSTRACT

Intensive irrigation and nitrogen (N) fertilization are often linked to low N-fertilizer efficiency, and to high emissions of the greenhouse gas nitrous oxide (N_2O). Efficient irrigation systems (e.g. subsurface drip irrigation [SDI]) combined with N-fertigation in a no-till agroecosystem can promote N-use efficiency, thereby curbing N_2O emissions without depressing crop yield. Yet, crop type and SDI plant settings (and management) such as dripline spacing may determine the agronomic and environmental performance of SDI. In this two-year field study on maize (*Zea mays* L.) - soybean (*Glycine max* [L.] Merr.) rotation with conservation agriculture management (no-till and cover crops), we investigated the effects of three different irrigation/fertilization systems (SDI with a narrow dripline spacing (70 cm) + fertigation with ammonium sulphate, SDI with a large dripline spacing (140 cm) + fertigation with ammonium sulphate, and sprinkler irrigation [SPR] + granular urea application) on yield, N-fertilizer efficiency, and N_2O emissions in a fine-textured soil. We hypothesized that SDI systems (especially with narrow dripline distance) would increase yield and mitigate N_2O compared with SPR, and particularly for maize due to its higher water and nutrient demand. We found that SDI increased maize yield (+31%) and N-fertilizer efficiency (+43–71%). These positive results were only observed during the drier year in which irrigation supplied ca. 80% of maize water requirements. The narrower dripline spacing mitigated N_2O emissions compared with sprinkler irrigation (by 44%) and with the wider spacing (by 36%), due to a more homogeneous distribution of N in soil, and to a lower soil moisture content. Soybean yield and N-use efficiency were not affected by the irrigation systems. We also found that SPR enhanced cover crop residue decomposition, thus promoting the release of C and N into the soil and increasing N_2O emissions. Overall, our study provides important insights on key management decisions that define the sustainability of novel irrigation systems; in particular SDI with a 70 cm dripline distance should be promoted for maize to increase productivity and decrease N_2O emissions in fine-textured soils.

1. Introduction

Nitrous oxide (N_2O) is a potent greenhouse gas with a global warming potential 273 times greater than that of CO_2 on a 100-year time horizon (Allan et al., 2021), and is the most dominant ozone-depleting substance of the 21st century (Ravishankara et al., 2009). Agriculture is the largest source of anthropogenic N_2O emissions (Montzka et al., 2011; Syakila and Kroeze, 2011). Although N_2O production in soils may occur through several biotic and abiotic processes such as nitrifier denitrification (Wrage-Mönnig et al., 2018), co-denitrification (Spott and Florian Stange, 2011), chemodenitrification (Van Cleemput, 1998), and dissimilatory nitrate reduction to ammonium (Rütting et al., 2011), two processes are considered the main sources: nitrification (Skiba and Smith, 1993) and denitrification (Firestone et al., 1980). All these processes may be considerably affected by agroecosystem management practices, including application of N-fertilizers, irrigation system, as

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well as crop type and residue management (Snyder et al., 2007; Perego et al., 2016; Wagner-Riddle et al., 2017; Lin and Hernandez-Ramirez, 2020).

Conventional irrigation techniques (e.g. furrow and sprinkler [SPR]) combined with a single application of N-fertilizer at a high rate are known to boost N_2O emission (Mehmood et al., 2019). This is mainly due to the simultaneous high moisture and mineral N availability in the soil, promoting N_2O emissions from nitrification and denitrification (Tian et al., 2017; Millar et al., 2018). This combination of practices is widespread in conventional agricultural systems due to easy implementation (Bierman et al., 2012; Ayyub et al., 2019). Yet, it can also lead to high N losses through leaching because of the mismatch between soil N availability and plant uptake in some pedoclimatic conditions and crop stages (Black et al., 1985; Grant et al., 2012; Xia et al., 2017), thereby reducing N-use efficiency (NUE).

Micro-irrigation systems (i.e. surface and subsurface drip irrigation [SDI]) combined with split N-fertilization through fertigation have been suggested as a measure to reduce N_2O emissions from soils and increase NUE (Li et al., 2018; Sandhu et al., 2019; Kuang et al., 2021). This is mainly a consequence of partial soil wetting and enhanced plant N-uptake throughout the growing season (Kallenbach et al., 2010; Mehmood et al., 2019). Particularly, SDI can further reduce N losses compared with surface drip irrigation by optimizing spatial N-fertilizer application (as released near the rhizosphere), and decreasing surface soil wetting (Kallenbach et al., 2010; Maris et al., 2015; Wei et al., 2018). However, recent studies reported higher N_2O emissions under micro-irrigation systems compared with conventional methods because of more frequent soil drying-wetting cycles, which increases soil N mineralization rates (Kuang et al., 2018). These inconsistencies emphasize the need for further investigations.

Crop type/sequence is recognized as a major driver of agro-environmental performance. For instance, the response of yield, NUE and N_2O emissions to different irrigation and fertilization systems vary strongly depending on the crop physiological groups (e.g. Gramineae vs. leguminous plants). Indeed, since leguminous crops such as soybean can meet a large part of their N demand through biological N fixation, they often do not require N fertilization (Liu et al., 2011), leading to lower N_2O emissions than non-leguminous crops (Schmeer et al., 2014). Moreover, Gramineae species with C4 photosynthetic pathway (e.g. maize) have higher water and NUE compared with C3 species such as soybean (Ghannoum et al., 2010). Accordingly, the potential benefits of micro-irrigation systems for improving yield and NUE may be more pronounced for maize than for soybean.

In SDI systems, dripline spacing affecting dynamics of irrigation water distribution is one of the key management decisions with potential consequences for N losses, crop yields, and NUE. Dripline distance is usually set as an integer multiple of the crop row spacing, which may vary depending on crop-soil variables, and ranges between 70 and 300 cm (Lamm et al., 1997; Lamm, 2016; Lee et al., 2018). By lowering the amount of water and N per unit of soil volume delivered to the rooting zone at each irrigation, an appropriate dripline spacing to match the crop row spacing (e.g. 70 cm in maize) could further improve water and N spatial distribution compared to wider dripline spacing. On an area basis, it could be argued that a wider spacing could create larger dry areas, thus reducing area-scaled N_2O emissions. However, considering the non-linear relationship between N_2O emissions and water and N availability (Davidson, 1991; Kim et al., 2013; Shcherbak et al., 2014), the N_2O hotspots in the wet areas with wide dripline spacing (with much higher water and N application per unit of soil volume) could be much greater than the low fluxes from the dry areas generated with this system. Therefore, reducing dripline distance may increase yields and NUE as well as reduce N losses, although this also implies higher system costs (Bosch et al., 1998; Sorensen et al., 2013).

Cover crop residue decomposition and mineralization after incorporation into or onto the soil provides extra-C and -N to soil microorganisms (Maris et al., 2021), promoting N_2O emissions and affecting the yield of the following crop (Fiorini et al., 2020; Martínez-García et al., 2021). Since soil water content and wetting–drying cycles are strong regulators of fresh residue decomposition (Schmidt et al., 2016), contrasting irrigation systems may determine different cover crop decomposition rates, resulting in differences in soil C and N availability. This could be one of the main mechanisms by which irrigation practices regulates NUE in crop rotations including cover crops. However, no prior studies have examined how different irrigation methods control cover crop decomposition rate and the associated impacts on N_2O emissions and crop yield.

In a two-year field study, we investigated the effect of three irrigation systems (subsurface drip irrigation with a narrow dripline spacing [SDI70] vs. subsurface drip irrigation with a wide dripline spacing [SDI140], vs sprinkler irrigation [SPR]) on yield, N_2O emissions and NUE of maize and soybean. We hypothesized that: (1) micro-irrigation techniques (SDIs) combined with split fertigation increase crop yield and NUE while reducing N_2O emissions compared with SPR; (2) the positive effect of SDI on crop yield, NUE and N_2O emissions is stronger on maize than on soybean; (3) among SDI systems, a narrow dripline spacing (70 cm) increases crop yield and NUE while reducing N_2O emissions compared to a wide dripline spacing (140 cm); and (4) SDI systems reduce litter decomposition rate and, therefore, curb N_2O emissions.

2. Materials and methods

2.1. Site description

We set a two-year field experiment at CERZOO experimental research station in Piacenza (45°00′18.0′N, 9°42′12.7′E; 68 m above sea level), Po Valley, Northern Italy. The soil is a fine, mixed, mesic Udertic Haplustalfs (Soil Survey Staff, 2014), with a silty clay texture. The physico-chemical characteristics of the soil in the top 0–30 cm layer were: sand 123 g kg^{-1}; silt 466 g kg^{-1}; clay 412 g kg^{-1}; pH H_2O 7.6; organic matter concentration 33 g kg^{-1}; bulk density 1.30 g cm^{-3}; soil total N 1.9 g kg^{-1}; available P (Olsen) 43 mg kg^{-1}; exchangeable K (NH_4^+ Ac) 292 mg kg^{-1}; and cation exchange capacity 32 $cmol^+$ kg^{-1}. The site is characterized by a temperate climate (Cfa as Köppen classification), with average annual temperature of 13.2 °C and annual rainfall of 837 mm (average of 2000–2020 period). Average temperature and rainfall during maize and soybean growing season (average of 2000–2020 period) are 21.5 °C and 300 mm, respectively. Meteorological data during the experiment were collected from an automated meteorological station placed near the experimental field. Growing season cumulative rainfall was calculated as the sum of daily cumulative rainfall between sowing and harvest of main crops.

2.2. Experimental design, treatments and crop management

A subsurface drip irrigation (SDI) plant was designed and established in April 2014. In detail, two SDI sectors, each of 13400 m^2, were arranged within the selected experimental field. With GPS positioning drip pipes and laterals were buried to 45 cm below the soil surface in all sectors, while the inter-row spacing was 70 cm in one sector and 140 cm in the other sector, thus defining two different structural set-ups of the plant as two SDI experimental levels: (i) subsurface drip irrigation with inter-row of 70 cm (SDI70), and (ii) subsurface drip irrigation with inter-row of 140 cm (SDI140). Since sprinkler irrigation (SPR) is the most common irrigation systems of the area (Po Valley, right side of the Po river), an additional sector of the field (alongside with the two sectors with SDI) were sprinkler irrigated as control, keeping a 3 m buffer zone between SDI and SPR sectors. Irrigation in the SPR system was carried out with a hose reel system, which consists of a single portable sprinkler head spraying water in a circular pattern. The irrigation flow rate was 3200 L min^{-1} and the lateral length was 400 m.

Prior to set up the SDI plant, the soil was managed with conventional agriculture practices (i.e. moldboard plowing at 40-cm depth and rotary harrowing at 15–20-cm depth, no cover crops, no crop residues left). Starting from April 2014 right after SDI setup, conservation agriculture has been adopted (i.e. no-till plus cover crops and residue management). From May 2014 to October 2018, the crop sequence was a maize-soybean crop rotation. The present field experiment started in December 2018, four years after the conversion to conservation agriculture, so excluding any interactions due to possible effects of the transition (Fageria et al., 2007; Derpsch et al., 2014; Pittelkow et al., 2015) and maintained until December 2020. Throughout the experiment, soybean (*Glycine max* [L.] Merr.; cv. Xonia) and maize (*Zea mays* L.; hy. LG 30.597) were planted as main crops for all three irrigation systems, both simultaneously present on the field in each year by splitting the three main sectors (SDI70, SDI140 and SPR) into six sub-sectors of 6700 m^2 each. Therefore, the following six treatments were established: SDI70 with maize (SDI70-M), SDI70 with soybean (SDI70-S), SDI140 with maize (SDI140-M), SDI140 with soybean (SDI140-S), SPR with maize (SPR-M) and SPR with soybean (SPR-S). The experimental field and treatment design are displayed in Fig. S1. The maize-soybean sequence was kept in all sectors, so that maize was planted in 2020 in sectors where soybean was planted in 2019, and viceversa. In 2019, maize and soybean were planted on June 6th because of high cumulative rainfall during the April-May period (269 mm; Fig. S2), which resulted in excessive soil moisture content for planting, compared to the same period in 2020 (168 mm; Fig. S2), when both crops were planted earlier (on April 23rd). In both years, crop rows were aligned on top of driplines thanks to GPS assisted planter. Right after harvesting the main crop (on 12th October in 2019 and on 24th September in 2020), a cover crop mixture including 26% (on weigh) rye (*Secale cereale* L.), 16% common oat (*Avena sativa* L.), 12% black oat (*Avena strigosa* Schreb.), 16% hungarian vetch (*Vicia pannonica* Crantz.), 20% common vetch (*Vicia sativa* L.), 3% crimson clover (*Trifolium incarnatum* L.), 2% berseem clover (*Trifolium alexandrinum* L.), and 5% tillage radish (*Raphanus sativus* L. subsp. *longipinnatus*) was sown each year at rate of 60 kg ha^{-1}. Approximately two weeks before sowing the following main crop, cover crops were chemically terminated by spraying Glyphosate [N-(phosphonomethyl) glycine] at the rate of 3 L ha^{-1} and residues were left onto the soil surface without mowing. Maize and soybean were sod-seeded after cover crop termination.

The experimental design consisted of three factors: (i) the irrigation system as the first factor, with three levels (SDI70, SDI140 and SPR); (ii) the crop type as the second factor with two levels (Soybean, S and Maize, M), which was nested within the irrigation factor; and (iii) the experimental year as the third factor, with two levels (2019 and 2020). As a result, the six irrigation system × crop type treatments were present simultaneously in both years. The number of pseudo-replicates - within each of the six sub-sectors - was four.

Irrigation water requirements during the maize and soybean cropping cycles were calculated for each treatment as follows: $ETc = Kc \times ET0$, where ETc is the theoretical crop evapotranspiration, ET0 is the reference evapotranspiration calculated by the FAO Penman-Monteith formula, while Kc is the single crop coefficient calculated according to the crop stages (Kc ini; Kc mid; and Kc end) (Allen et al., 1998). Partial soil wetting of the SDI system was taken into account multiplying Kc ini by the fraction of the soil surface wetted (Allen et al., 1998) (estimated as a 5%), which was based on visual estimation of surface soil wetting during irrigations (Hunsaker and Bronson, 2021). As a result, irrigations were performed every 10–14 days on SPR and every 3–4 days on SDI, on average. Irrigation-water use efficiency [iWUE (kg m^{-3})] was calculated as the ratio between grain yield (kg ha^{-1}) and supplied irrigation water (m^3 ha^{-1}). N-fertilization was only used in maize (both years). N-fertilizers were split and applied to maize in SDI treatments every 7–10 days as ammonium sulphate [$(NH_4)_2SO_4$] through the drip system with repeated applications of 40 kg N ha^{-1} each, totaling 280 kg N ha^{-1}. In maize SPR treatment, N-fertilizers were supplied as granular urea (CH_4N_2O), with two applications (140 kg N ha^{-1} each) at V2-V3 and at V8-V9 growth stages in both years, using a tractor with a fertilizer spreader. Urea incorporation into the soil under SPR treatments was promoted by a subsequent irrigation. We applied different types of N-fertilizer to compare an innovative (low-pressure) and efficient irrigation system combined with a renewable fertilizer for fertigation (ammonium sulphate), with a common irrigation/fertilization practice of Northern Italy (Sprinkler irrigation + Urea application).

The N-fertilizer rate was computed according to the estimated (predicted) N-balance, considering crop, soil, and climate variables (Grignani et al., 2007). In detail, the N rate to be supplied with fertilizer was calculated as the difference between the estimated crop N-uptake (considering reasonable target yields for the area) and the estimated available N in the soil. According to soil physical and chemical properties, estimated available N was calculated as follows (Grignani et al., 2003):

$$Na = Nm - Nl \pm Nr + Ns - Nid \tag{1}$$

where (i) *Nm* is the estimated mineralized N according to organic matter and total N concentration, soil texture, soil C:N ratio and bulk density; (ii) *Nl* is the estimated rate of N leached, as a function of rain and irrigation rates; (iii) *Nr* is the residual N, estimated according to previous crops and cover crops; (iv) *Ns* is supplemental N from previous organic amendments (if any), atmospheric deposition and irrigation water; and (v) *Nid* is the immobilized and/or dispersed N. Full details about the estimated available N are reported in the supplementary material. Goodness of estimation was then verified by confirming the minor changes in soil total N and available pools at the end of the experiment.

2.3. *Yield measurements*

Yield components of maize and soybean crops were assessed by manually harvesting four areas of 10 m^2 per single sub-sector (8 and 50 plant per m^2 for maize and soybean, respectively). Plants were weighed and separated into grain and stover. A 100 g sub-sample of each grain and stover sample was oven-dried at 65 °C until constant weight to measure dry matter content. Soybean stover was measured at harvest, also collecting fallen leaves. Harvest index (HI) of maize and soybean was calculated as the ratio between grain yield and total biomass at harvest on a dry matter basis. Grain and total N-uptake were calculated by multiplying grain yield and grain yield + stover biomass by their N-concentrations, respectively. N-concentrations of grain and stover were determined by the Dumas combustion method with an elemental analyzer varioMax C:N (VarioMax C:NS, Elementar, Germany).

Regarding cover crops, four areas of 3 m^2 each were randomly chosen within each sub-sector by manually harvesting plants and weighed to assess total aboveground biomass. Sub-samples were collected to calculate dry matter content and C and N concentration as described above for the main crops. N concentration and C:N ratio of CCs at T0 were used to compute litter-DM and -N decay rate at the initial steps of decomposition.

2.4. *N-fertilization efficiency measurements*

The three following N-efficiency parameters were calculated for each treatment according to López-Bellido and López-Bellido (2001): (i) N-use efficiency (NUE; kg kg^{-1}) as the ratio of grain yield to N supply, where N supply is the sum of soil nitrate (NO_3^-) at sowing, mineralized N and N-fertilizer; (ii) N harvest index (NHI; %) as the ratio of N in grain to N in total plant biomass; and (iii) N-utilization efficiency (NU_tE; kg kg^{-1}) as the ratio of grain yield to total plant N-uptake. The actual mineralized N was calculated at the end of the experiment according to Feichtinger et al. (2004) as follows:

$$Nm = Nd + Np - Nf \tag{2}$$

where (i) *Nm* is the net-N-mineralisation (kg N ha^{-1}); (ii) *Nd* is the difference in inorganic N in the soil (0–30 cm) between autumn and spring, (kg N ha^{-1}); (iii) *Np* is the N uptake by plants (kg N ha^{-1}); and (iv) *Nf* is the inorganic N fertilisation through mineral fertiliser (kg N ha^{-1}).

2.5. Nitrous oxide sampling and flux estimates

The close chamber method (Smith et al., 1995; Moretti et al., 2020) was used to assess N_2O direct emissions from soils from December 2018 to December 2020. Cylindrical static chambers (40 cm diameter and 25 cm high) were made of polyvinyl chloride (PVC) with a light color to reduce the impact of direct radiating heat during samplings. The chambers (four per treatment) were inserted into the soil by fitting them into stainless steel rings, which were positioned 10 cm into the soil prior to the beginning of the experiment. Rings were temporarily removed exclusively for specific operations (i.e. planting, fertilizing and harvesting) in order to avoid the effect of soil disturbance on N-fluxes. Chambers were centered at 17.5 cm and 35 cm from driplines (and rows) for SDI70 and SDI140 respectively, as a way to manage different dripline spacing (Fig. S1). In SPR sectors, chambers were centered in inter-row (Fig. S1). A battery-operated fan was installed inside each chamber to maintain air mixing. Gas sampling took place once per month during winter periods (due to the low soil temperatures and absence of intense freeze-thaw cycles) up to twice/three times per week following N-fertilizer applications. The total number of measurements was 40 (20 per year). As described by Maris and et al., (2015, 2018) sampling was carried out in the morning between 09:00 and 12:00 h to reduce diurnal variation in flux patterns. Alongside N_2O sampling, the temperature outside and inside the chambers was measured with digital thermometers. Six ambient air samples were taken at the moment of chamber closure (at 0 min) and then headspace air samples were taken at 15 and 30 min after enclosure of chambers. A 100 mL syringe was used to collect 60 mL air samples; a volume of 30 mL was discarded to purge the syringe and the remaining gas was transferred to 12 mL pre-evacuated LabcoExetainer® glass vials sealed with butyl rubber stoppers. Subsequently, air samples were analyzed by gas chromatography (Agilent 7890 A with a Gerstel Maestro MPS2 autosampler) equipped with an electron capture detector for N_2O quantification. The linear increase of N_2O concentration (after temperature corrections) within the chamber headspace was used to calculate daily fluxes when linearity was verified ($R^2 > 0.9$). Emission rates were estimated as the slope of the linear regression between concentration and time and from the ratio between chamber volume and soil surface area (MacKenzie et al., 1998). Annual cumulative N-N_2O emissions were calculated by linear interpolation of the whole annual sets of fluxes, while growing season cumulative N-N_2O emissions were calculated for each experimental year by linear interpolation of fluxes measured from sowing to harvest.

2.6. Soil properties

Four soil samples were collected to determine mineral N-content from each sub-sector once per month in winter periods, and up to twice/three times per week after N-fertilizer applications. Each soil sample consisted of 3 soil sub-samples taken at 0, 17.5 and 35 cm from the dripline in SDI70 treatments, at 0, 35 and 70 cm from the dripline in SDI140 treatments, and at 0, 35 and 70 cm from the crop row in SPR treatments, as a means to account for the different N-fertilizer spatial patterns (Fig. S1). The soil cores were taken at 30 cm depth and then divided into two layers: 0–10 and 10–30 cm. Finally, four composite soil samples were obtained per each depth, sampling date, and sub-sector. Soil samples were immediately transported to the laboratory for NO_3^-, ammonium (NH_4^+) and water content analyses. The soil NO_3^- and NH_4^+ concentrations were analysed using 5 g of homogeneously mixed soil extracted with 20 mL of K_2SO_4 (0.5 M) and pipetted into 96-well quartz microplates. Nitrate-N and NH_4^+-N were then determined with dual-wavelength UV spectroscopy (275, 220 nm) on acidified (HCl 1 M) samples. Gravimetric water content (GWC) in the 0–10 cm soil layer was measured at each gas sampling by oven drying soil samples at 105 °C for 24 h. The cylinder method (Gómez-Paccard et al., 2015) was used to assess soil bulk density at 0–10 cm depth. Volumetric water content (VWC) at 0–10 cm depth was calculated by multiplying GWC and soil bulk density, while soil porosity was determined assuming mineral soil particle density of 2.65 g cm^{-3} (Porta Casanellas and López-Acevedo Reguerín, 2008). Field capacity was calculated as described by Saxton and Rawls (2006). Water-filled pore space (WFPS) was calculated as the ratio of VWC and soil porosity (Danielson and Sutherland, 1986). The average growing season soil WFPS, NO_3^- and NH_4^+ concentrations were calculated as weighted means of data measured from planting to harvest.

2.7. Litter and litter-N decay rate *k*

In both years during maize and soybean seasons, nylon litter-bags (40 × 30 cm; 1 mm size) were filled with 50 g of cover crop residues previously dried at 65 °C until constant weight (Bocock and Gilbert, 1957). These litter-bags were randomly placed on the soil surface after cover crops termination. For each irrigation sub-sector, four litter-bags were collected at each sampling time (at 8, 18, 30, 46, 65, 90, 121 and 156 days after positioning). Then, litter-bags were dried at 65 °C and weighed for estimating mass decay rate. N-concentration was determined by the Dumas combustion method described above and corrected considering ash-content as described by Christensen (1985). Litter-DM and litter-N decay rate *k* (day^{-1}) were calculated assuming first-order kinetics. Average growing season litter-DM and litter-N decay *k* were calculated as weighted means of data measured from sowing to harvest of main crops.

2.8. Statistical analyses

A linear mixed model was applied to study the effect of the irrigation treatment, crop and year on (i) maize and soybean grain yield and total biomass, (ii) N-uptake and N-efficiency parameters, (iii) cumulative N_2O emissions, and (iv) growing season average soil NO_3^- and NH_4^+ content. The subplot within sub-sectors was considered as a random factor. We used linear mixed effects models to account for the lack of independence among the individual units of observation. The measured variables were checked for normality using the Shapiro-Wilk test and for homogeneity of variances with the Levene's test.

A repeated measures ANOVA was conducted, separately for the two experimental years, on litter and litter-N decay *k* with irrigation, crop and time as fixed factors and replicate as random effect. When the ANOVA assumptions were violated, data were log transformed prior to analysis and back-transformed after the post hoc test. Tukey's honestly significant difference (HSD) was used as post hoc to test significant differences among treatments with a *p*-value of 0.05 as threshold. The correlation analysis was performed to assess the relationship between all variables measured or calculated in the experiment, using the non-parametric Spearman rank coefficient (ρ). A *p*-value of 0.05 was considered significant for the test. We used R 4.0.3. (R Core Team, 2020) with nlme (Pinheiro et al., 2013), multcomp (Hothorn et al., 2007), and factoextra (Kassambara and Mundt, 2020) packages for the linear mixed effect models, HSD tests and Spearman's rank correlations, respectively.

3. Results

3.1. Environmental conditions, water parameters and soil mineral N pools

Average daily air temperature during the two-year period ranged from 1.2° to 25.0°C, while annual rainfall was 1020 mm in 2019 and 949 mm in 2020 (Fig. S2). Despite the similar annual rainfall, the two years had a very different rainfall pattern during the maize and soybean growing season period. In detail, growing season cumulative rainfall was 194 mm in 2019, while the corresponding value in 2020 was 347 mm (+79%) (Fig. S2; Table 1). Cumulative growing season ETc under maize SDI treatments was 429 mm in 2019 and 503 mm in 2020 (Table 1). Water applied to maize via irrigation was 243 mm in 2019 and 163 mm in 2020 (−33%) (Table 1). Therefore, total water applied to maize under SDI treatments was 437 mm in 2019 and 510 mm in 2020 (Table 1). Further details about irrigation rates and ETc for SPR treatments and soybean are reported in (Table 1).

Water-filled pore space was generally higher under SPR than under SDI (Fig. S3). Specifically, average WFPS for the growing season was 54% in 2019 and 58% in 2020 under SDI, while it was 61% in 2019 and 64% in 2020 under SPR (Fig. S3). Among SDI treatments, the narrow dripline distance slightly reduced average growing season WFPS from 55% to 54% in 2019 and from 60% to 57% in 2020 compared with SDI140 (Fig. S3). However, the effect of dripline distance on average growing season WFPS was more pronounced on maize in 2019 (Fig. S3): SDI70-M reduced WFPS by 7% compared with SDI140-M. Overall, average growing season WFPS was lower in 2019 (57%) than in 2020 (61%).

Concentrations of NO_3^- and NH_4^+ during the growing season in the 0–10 and 10–30 cm soil layers were affected by the three-factor interaction (Table 2). Nitrate concentration was significantly higher under SDI140-M than under SDI70-M in the 0–10 cm soil layer in 2019, while both SPR-M and SDI140-M increased NO_3^- concentration compared with SDI70-M in the 10–30 cm soil layer during the same year. No difference between treatments was found in 2020 (Fig. 1a).

NO_3^- concentration in the 0–10 cm soil layer was higher under SDI-S treatments than under SPR-S in 2019, whereas only SDI140-S increased soil NO_3^- content compared with SPR in 2020 (Fig. 1b). SPR-S reduced NO_3^- concentration in the 10–30 cm soil layer compared with SDI140-S in 2019 (Fig. 1b).

Ammonium concentration was often higher for SPR-M in 2019 (+67% and +32% in the 0–10 cm layer compared with SDI70-M and SDI140-M, respectively) (Fig. 1c). SDI70-M significantly reduced average soil NH_4^+ concentration in both soil layers compared with other treatments in 2019 (Fig. 1c). In 2020, NH_4^+ soil concentration was significantly higher under SPR-M than under SDI treatments only in the 0–10 cm layer (Fig. 1c). No differences were found between soybean treatments regarding NH_4^+ concentration in the 0–10 cm soil layer for both years, however SDI140-S increased NH_4^+ content in the 10–30 cm soil layer in 2020 (Fig. 1d).

Table 1
Growing season water parameters for each treatment in 2019 and in 2020 (subsurface drip irrigation with dripline distance of 70 cm on maize [SDI70-M], subsurface drip irrigation with dripline distance of 70 cm on soybean [SDI70-S], subsurface drip irrigation with dripline distance of 140 cm on maize [SDI140-M], subsurface drip irrigation with dripline distance of 140 cm on soybean [SDI140-S], sprinkler irrigation on maize [SPR-M] and sprinkler irrigation on soybean [SPR-S]).

	Treatment	Cumulative rainfall (mm)	Total irrigation (mm)	Rainfall + irrigation (mm)	Cumulative ETc (mm)
2019	SDI70-M	194	243	437	429
	SDI70-S		182	376	371
	SDI140-M		243	437	429
	SDI140-S		182	376	371
	SPR-M		295	489	481
	SPR-S		231	425	418
2020	SDI70-M	347	163	510	503
	SDI70-S		101	448	439
	SDI140-M		163	510	503
	SDI140-S		101	448	439
	SPR-M		200	547	540
	SPR-S		132	479	474

Table 2
Analysis of variance of yield components, N-fertilizer efficiency parameters, irrigation-water use efficiency, N_2O emissions and soil N pools as affected by year (Y), irrigation system (I), crop (C) and the interactions between factors.

Source of variation	Grain Dry Yield	Total Dry Biomass	HI	Grain N-uptake	Total Biomass N-uptake	NUE	NHI	NUtE	iWUE	Annual cumulative N_2O emission	Growing season cumulative N_2O emission	0–10 cm growing season NO_3^-	10–30 cm growing season NO_3^-	0–10 cm growing season NH_4^+	10–30 cm growing season NH_4^+
p-value															
Year (Y)	< 0.001	**0.005**	< 0.001	< 0.001	< 0.001	0.579	**0.022**	0.211	< 0.001	**0.030**	**0.011**	< 0.001	**0.005**	< 0.001	< 0.001
Crop (C)	< 0.001	< 0.001	< 0.001	< 0.001	**0.004**	**0.055**	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	0.221	**0.008**	< 0.001	< 0.001
Irrigation (I)	0.175	0.135	**0.002**	**0.009**	< 0.001	< 0.001	**0.002**	< 0.001	< 0.001	< 0.001	< 0.001	**0.001**	**0.040**	< 0.001	0.004
Y×C	< 0.001	< 0.001	**0.041**	**0.020**	**0.019**	< 0.001	**0.019**	**0.005**	< 0.001	**0.003**	**0.015**	0.138	0.810	< 0.001	0.191
Y×I	**0.002**	0.211	< 0.001	0.803	0.175	< 0.001	< 0.001	< 0.001	0.176	0.473	0.567	0.111	**0.010**	0.850	0.670
C×I	< 0.001	0.109	< 0.001	0.157	0.492	**0.002**	**0.002**	< 0.001	< 0.001	0.234	0.125	**0.014**	**0.011**	0.290	0.436
Y×C×I	< 0.001	**0.036**	**0.006**	**0.014**	**0.003**	**0.007**	**0.038**	< 0.001	< 0.001	0.347	0.156	**0.037**	**0.005**	**0.020**	**0.002**

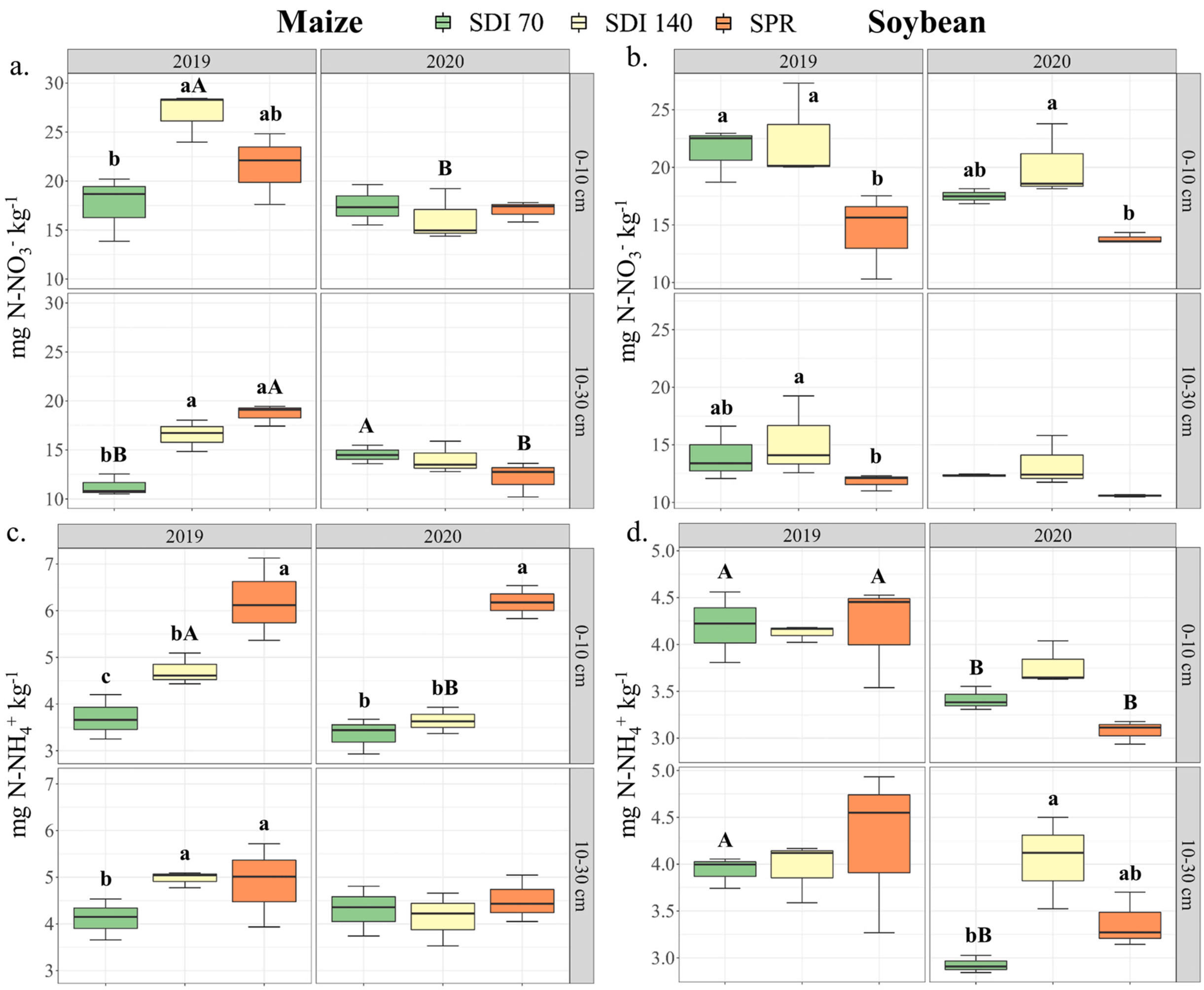

Fig. 1. Box plots of N-NO_3^- concentration on maize (a) and soybean (b); N-NH_4^+ concentration on maize (c) and soybean (d) in the 0–10 cm and 10–30 cm soil layers as affected by year (2019 and 2020) and irrigation system (subsurface drip irrigation with dripline distance of 70 cm [SDI70], subsurface drip irrigation with dripline distance of 140 cm [SDI140] and sprinkler irrigation [SPR]). The bottom and top of each box represent the lower and upper quartiles respectively, the line inside each box shows the median and whiskers indicate minimal and maximum observations. Capital letters indicate differences among years within the same irrigation system; lowercase letters indicate differences among irrigation systems within the same year. Please note the scale differences in the Y-axis between crops.

3.2. Yield components and efficiency parameters

All the yield and efficiency parameters (i.e. NUE, NHI, NUtE, and iWUE) were affected by the three-factor interaction (Table 2) and are reported in Table 3. SDI generally increased maize grain yield compared with sprinkler irrigation in 2019 (+31%). In addition, SDI70 had higher NUE, NHI and NUtE (while SDI140 had only higher NUtE) than SPR for maize in 2019. Maize HI was reduced by SPR compared with SDI treatments in 2019. No differences were found between SDI70-M and SPR-M during 2020 in terms of N-efficiency parameters, while SDI140-M had lower NUE and NUtE than SPR-M and SDI70-M in 2020. SPR-M and SDI70-M outyielded SDI140-M in 2020 (+25% and +16% respectively). Both SDI70-M and SPR-M significantly increased grain yield in 2020 compared with 2019. Moreover, SPR increased HI of both soybean and maize in 2020 compared with 2019. Conversely, soybean grain yield and N-efficiency parameters were not affected by the irrigation treatments or years. Total biomass was lower for SDI140-M than for SDI70-M and SPR-M in 2020, while no difference between treatments occurred in 2019. Similar to grain yield, total biomass under SDI70-M and SPR-M was higher in 2020 than in 2019. HI was higher in 2020 than in 2019 under SPR-M and SPR-S.

Grain and total biomass N-uptake were not affected by the treatments, but it was generally higher in 2020 than in 2019.

Irrigation-water use efficiency of maize was higher under SDI treatments than under SPR in 2019, whereas both SPR-M and SDI140-M had lower iWUE compared with SDI70-M in 2020. No differences were found between soybean treatments in terms of iWUE in both 2019 and 2020.

3.3. N_2O fluxes and cumulative emissions

The daily average fluxes ranged from 0.00 to 0.52 kg $\text{N-N}_2\text{O}$ ha^{-1} d^{-1} during the two experimental years, and the highest value was measured in 2020 on SDI140-M (Fig. 2c). In 2019, N_2O emissions remained low until cover crops were terminated and irrigations (as well as fertilizations in maize) were carried out in late June. Then, a major emission peak occurred following the two urea applications under SPR-M and three emission peaks were observed after fertigation events under SDI70-M and SDI140-M (Fig. 2a). Several emission peaks were observed after cover crops termination and irrigations in 2019 under soybean treatments, especially in SDI140-S and SPR-S (Fig. 2b). In 2020, N_2O emission peaks were amplified (exclusively for maize) compared with previous year and occurred earlier (by the end of May), as a consequence of earlier sowing, fertilizations, and irrigations dates (Fig. 2c and d). Two major peaks were observed in all maize treatments following urea applications or fertigations in 2020 (Fig. 2c). N_2O emissions increased

Table 3

Grain dry yield (Mg ha^{-1}), total dry biomass (Mg ha^{-1}), harvest index (%), grain N-uptake (kg ha^{-1}), total biomass N-uptake (kg ha^{-1}), nitrogen use efficiency (NUE; kg kg^{-1}), nitrogen harvest index (NHI; %), nitrogen utilization efficiency (NUtE; kg kg^{-1}) and irrigation-water use efficiency (iWUE; kg m^{-3}) as affected by the interaction between year, (2019 and 2020) irrigation system (subsurface drip irrigation with dripline distance of 70 cm [SDI70], subsurface drip irrigation with dripline distance of 140 cm [SDI140] and sprinkler irrigation [SPR]) and crop (maize and soybean). Capital letters indicate differences among years within the same irrigation system and crop; lowercase letters indicate differences among irrigation system within the same year and crop.

Source of variation			Grain Dry Yield (Mg ha^{-1})	Total Dry Biomass (Mg ha^{-1})	HI (%)	Grain N-uptake (kg ha^{-1})	Total Biomass N-uptake (kg ha^{-1})	NUE (kg kg^{-1})	NHI (%)	NUtE (kg kg^{-1})	iWUE (kg m^{-3})
Year x Irrigation x Crop											
2019	Maize	SDI-70	11.9 a B	20.8 a B	57 a A	151 a B	211 a B	31.2 a A	72 a A	56.4 a A	4.99 a B
		SDI-140	11.9 a A	22.0 a A	54 a A	153 a A	239 a B	24.9 b A	64 ab A	49.7 b A	4.88 a B
		SPR	9.1 b B	22.3 a B	41 b B	146 a B	264 a A	23.3 b B	55 b A	34.7 c B	3.09 b B
	Soybean	SDI-70	3.3 a A	10.6 a A	31 a A	213 a A	253 a A	33.9 a A	85 a A	13.0 a A	1.64 a B
		SDI-140	3.6 a A	11.3 a A	32 a A	230 a A	269 a B	22.1 b A	86 a A	13.4 a A	1.79 a B
		SPR	3.8 a A	12.1 a A	31 a B	239 a A	292 a A	29.4 a A	82 a B	12.9 a A	1.52 a B
2020	Maize	SDI-70	14.6 a A	26.3 a A	55 a A	197 a A	306 a A	31.9 a A	65 a B	47.9 a B	8.95 a A
		SDI-140	11.7 b A	22.6 b A	52 a A	178 a A	284 a A	25.6 b A	63 a A	41.2 b B	7.19 b A
		SPR	13.6 a A	26.4 a A	52 a A	189 a A	292 a A	32.5 a A	65 a A	47.0 a A	6.82 b A
	Soybean	SDI-70	3.3 a A	10.0 a A	33 a A	219 a A	256 b A	21.0 b A	86 a A	12.9 a A	2.73 a A
		SDI-140	4.4 a A	11.5 a A	38 a A	282 a A	321 a A	23.9 b A	89 a A	13.8 a A	3.66 a A
		SPR	4.4 a A	10.7 a A	41 a A	279 a A	320 a A	32.4 a A	88 a A	13.8 a A	2.94 a A

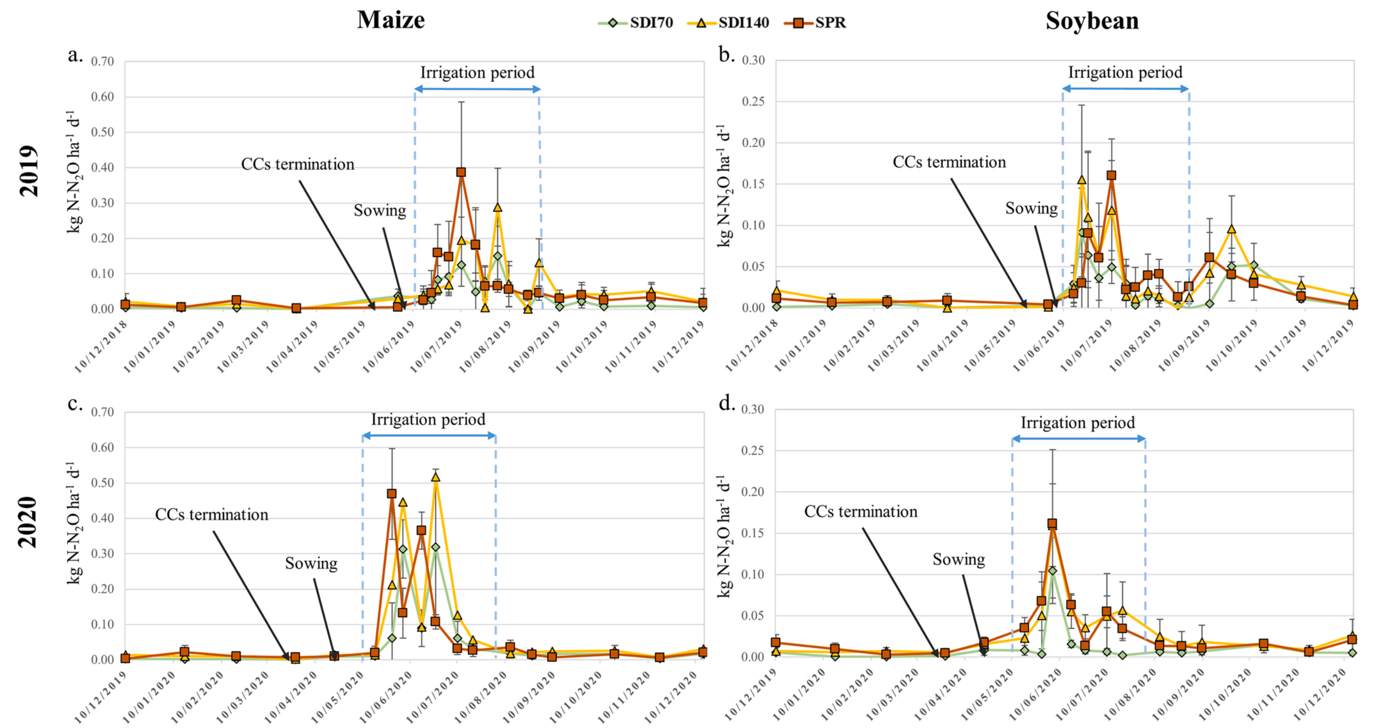

Fig. 2. Daily fluxes of N_2O on maize and soybean during the experiment (from December 2018 to December 2020) as affected by irrigation systems (subsurface drip irrigation with dripline distance of 70 cm [SDI70], subsurface drip irrigation with dripline distance of 140 cm [SDI140] and sprinkler irrigation [SPR]). Error bars in the figure represent standard deviation. Please note the scale differences in the Y-axis between crops.

after cover crops termination and irrigations under soybean treatments in 2020 (Fig. 2d).

Annual and growing season cumulative N_2O emissions were affected by irrigation and by the interaction between crop and year (Table 2). Specifically, SDI70 had lower N_2O emissions than SDI140 and SPR in both annual (7.2 kg ha^{-1}; −44% and −36% respectively) and growing season (5.1 kg ha^{-1}; −44% and −39% respectively) cumulative emissions (Table 4). During 2020, N_2O emissions were significantly higher than those in 2019 on maize, whereas no differences between years were found for soybean (Table 4).

3.4. *Litter and litter-N decay rates*

Litter and litter-N decay rates were significantly affected by the interaction between time, crop and irrigation (Table 5). Maize and soybean litter decay rates were generally lower in 2019 than in 2020. For both years and crop types, SPR increased litter and litter-N decay compared to SDI (Fig. S4). Raw data on N concentration and C:N ratio of CCs are not reported in our study, but those data were considered to determine litter-DM and -N decay rate.

Table 4
Annual and growing season cumulative N_2O emissions as affected by irrigation system (subsurface drip irrigation with dripline distance of 70 cm [SDI70], subsurface drip irrigation with dripline distance of 140 cm [SDI140] and sprinkler irrigation [SPR]) and the interaction between crop (maize and soybean) and year (2019 and 2020).

Source of variation		Annual cumulative N_2O emissions (kg N_2O ha^{-1} y^{-1})		Growing season cumulative N_2O emissions (kg N_2O ha^{-1})	
Irrigation					
SDI-70		7.2	b	5.1	b
SDI-140		12.9	a	9.1	a
SPR		11.2	a	8.3	a
Crop x Year					
Maize	2019	12.3	b	8.3	b
	2020	15.9	a	13.2	a
Soybean	2019	7.1	a	4.0	a
	2020	6.4	a	4.4	a

Table 5
Analysis of variance of litter decay rate *k* and litter-N decay rate *k* in 2019 and 2020 as affected by time (T), irrigation system (I), crop (C) and interactions between factors.

Source of variation	Litter decay *k* 2019 (d^{-1})	Litter decay *k* 2020 (d^{-1})	Litter-N decay *k* 2019 (d^{-1})	Litter-N decay *k* 2020 (d^{-1})
	p-value			
Time (T)	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**
Irrigation (I)	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**
Crop (C)	**0.001**	**< 0.001**	**0.020**	**< 0.001**
T × I	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**
T × C	**< 0.001**	**< 0.001**	**< 0.001**	**0.001**
C×I	**< 0.001**	**< 0.001**	**< 0.001**	**0.003**
T × C×I	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**

3.5. *Relationships between variables*

Grain yield, total biomass, grain N-uptake and total biomass N-uptake were positively correlated between them for both maize and soybean (Fig. S5a-b). Maize N-efficiency parameters were positively correlated between each other (Fig. S5a), whereas only NUtE was positively correlated with NHI on soybean (Fig. S5b). Among maize N-efficiency parameters, NHI and NUtE were negatively correlated with WFPS (Fig. S5a). Maize annual cumulative N_2O emissions were positively correlated with litter decay *k* and negatively correlated with NUtE, while growing season cumulative N_2O emissions were positively correlated with grain and total biomass N-uptake, cumulative rainfall and litter decay *k* (Fig. S5a).

Soybean annual and growing season cumulative N_2O emissions had positive correlations with grain yield, total biomass, N-uptake in grain and biomass, and litter-N decay *k* (Fig. S5b).

4. Discussion

4.1. Yield, N-efficiency and iWUE responses of maize and soybean to irrigation and N-fertilization method

The generally higher maize yield and NUE of SDI in 2019 compared to SPR suggests a potential higher capacity for this irrigation method to improve N exploitation and relocation in maize grain. The increased maize yield, NUE and iWUE of SDI observed in 2019 was likely because of: (i) reduced ETc under SDI than under SPR, as supported by the WFPS results, and (ii) more efficient water and N-fertilizer distribution, which are supplied together and directly close to the root zone in SDI, at 45-cm soil depth in our case. On the other hand, with SPR irrigation, water is applied on the top of the soil surface every 10–14 days in relatively high amounts, promoting high evaporation losses. Moreover, under SPR fertilization is performed with two applications of N-fertilizer (140 kg N ha^{-1} each), thus possibly leading to a mismatch between soil N availability and plant N demand. Hence, both these factors led to reduced irrigation- and N-use efficiency (Li et al., 2018; Sandhu et al., 2019). This is supported by the higher soil moisture under SPR during maize in 2019, and by the negative relationship between soil moisture and N-efficiency parameters. In addition, the two side dressings of N fertilizer in SPR (140 kg N ha^{-1} each) compared with the seven applications at 45 cm depth (40 kg N ha^{-1} each) in SDI, increased soil NH_4^+ concentration in the 0–10 cm layer, thus possibly promoting N_2O emissions via nitrification and, as a consequence, reducing NUE (Mosier et al., 1998). Interestingly, HI was lower under SPR-M than under SDI-M treatments in 2019. This was probably due to the common hose reel irrigation management, in which water is supplied in high amounts and with low frequency, thus leading to temporary water stress in plants. If this short, but still significant, water stress matches with high temperature, especially during pollen-shedding and silking stages, the sterile part of the spike will be increased (Hall et al., 1982). Lower seed yield and harvest index of maize have been previously reported under increasing severity of drought stress (Khalili et al., 2013). Lower irrigation rates coupled with shorter time intervals in SPR, which are uncommon in the region of this study, could have avoided these negative effects.

These results are in contrast with previous findings reporting no benefits of SDI in terms of maize yield compared to sprinkler irrigation (Valentín et al., 2020). However, in this study the authors also found an increase in water use efficiency of drip irrigated maize compared with sprinkler, underlining the importance of micro-irrigation systems to increase water productivity of crops with a high water demand. In addition, our findings are in agreement with those of Hanson and May (2004), observing higher processing tomato yield under SDI than under a sprinkler system with similar amount of applied water, and by Zhou et al. (2017) reporting higher maize grain yield and NUE under drip irrigation systems.

We also found that – despite no difference in terms of grain yield – a narrow dripline distance had higher NUE and NUtE than a wider distance in 2019. The lower soil mineral N content for both the 0–10 cm and 10–30 cm soil layers under SDI70-M indicate that narrowing dripline distance from 140 cm to 70 cm can enhance homogeneous spatial distribution of N into the soil. With a wider dripline distance, water and N outflow from a lower number of emitters per unit of soil volume. This may result into temporary “hot-spots” of high soil moisture (above soil water holding capacity), promoting N losses via leaching (and emissions of N as discussed below), and thereby causing a lower NUE. Indeed, volumetric water content was higher than estimated field capacity (39%) under SDI140-M on 21/06/2019 (42%) and on 25/06/2019 (40%), when fertigations/irrigations occurred.

The benefits for yield and N-efficiency parameters of micro-irrigation systems were not observed in 2020. This was probably because of the higher cumulative rainfall during the growing season of maize in 2020 (347 mm) than in 2019 (194 mm). The calculated ETc for the maize growing season period under SDI treatments was 503 mm in 2020 and 429 in 2019. This means that maize was less dependent on water application via irrigation in 2020, in which only 32% of the crop water requirements was supplied by irrigation (163 mm). On the other hand, the rate supplied with irrigation in 2019 was much higher (243 mm), representing 57% of the total crop water requirement. Therefore, the higher rainfall amount during such a sensitive period in 2020 provided most of the necessary water to support plant growth, and accordingly differences in water application methods became less important for plant yield. Hence, our study highlights that wet years may hinder the benefits for yield potential and N-fertilization efficiency of SDI. Nevertheless, SDI70-M increased iWUE compared with SDI140-M and SPR-M in 2020, confirming the general higher efficiency of this distance.

Contrary to maize, soybean grain yield was never affected by irrigation technique. This was probably because soybean water requirements are 9–12% lower than those of maize (Brouwer and Heibloem, 2010), which limits the importance of high-efficient irrigation methods. However, the soil NO_3^- content was generally lower in the surface soil under SPR-S than under both SDI treatments. This was probably because irrigation water was supplied with sprinkler at higher rates (per event) than that supplied with SDI, which may have increased water drainage throughout the 0–30 cm soil depth (towards deeper layers), thus increasing N losses through leaching.

4.2. Nitrous oxide emissions as affected by irrigation and N-fertilization method

Micro-irrigation combined with a narrow dripline distance mitigated N_2O emissions compared with sprinkler irrigation, in agreement with previous studies using surface and subsurface drip irrigation methods (Kallenbach et al., 2010; Maris et al., 2015; Wei et al., 2018) and with the recent meta-analyses conducted by Kuang et al. (2021) and Yangjin et al. (2021). Lower N_2O emission from soil under drip irrigated systems are usually due to partial soil wetting, lower soil moisture, and better temporal/spatial distribution of fertilizers. However, N_2O emissions were not decreased compared to sprinkler irrigation when a wide dripline distance was used. The N_2O reductions with a narrow distance are explained by the lower WFPS and soil mineral N concentration in 0–10 and 10–30 cm soil layers under SDI70-M in 2019. This probably prevented the establishment of anoxic conditions on the one hand, and deprived microorganisms of available N pools on the other hand, thus decreasing N_2O emissions derived from both nitrification and denitrification (Davidson, 1991; Senbayram et al., 2019). As previously discussed, reducing dripline distance to 70 cm promoted a better N exploitation and relocation in grain by providing water and N-fertilizer close to the root zone of each crop row, thus increasing uniformity of input distribution and absorption in time and space (Kallenbach et al., 2010; Maris et al., 2015; Wei et al., 2018). The non-uniform distribution of water and N-fertilizers in soil under SDI140-M may have resulted in the formation of flooded and N enriched “hot spots” near emitters, potentially boosting denitrification (Groffman et al., 2009). For SPR, the double application of urea increased soil mineral N in all soil layers at a higher rate than the numerous applications of ammonium sulphate under SDI70-M. This led to mismatching N availability and plant uptake under SPR (Black et al., 1985; Grant et al., 2012; Xia et al., 2017), thus increasing available N pools for nitrifiers (and subsequently to denitrifiers) right after urea applications (Senbayram et al., 2009). Different N-fertilizer types may have also affected N_2O emissions: in fact Hua et al. (1997) and Ghosh et al. (2003) found higher N_2O emissions with ammonium sulphate application compared with urea. These results underline the potential of SDI for limiting N_2O emissions, which may be reduced even further by applying urea via fertigation. However, ammonium sulphate can be obtained through ammonia stripping processes using organic substrates, while urea is synthetized through the Haber-Bosch process. Thus, the reduction in N_2O emission by using urea can be offset by the well-documented environmental impact of the latter process (Bicer et al., 2017).

As hypothesized, cover crop decomposition was affected by the irrigation systems, in turn regulating the emission of N_2O. Both litter and litter N decay rates were higher under SPR compared with SDI70 and SDI140, probably because the application of water on the top of the cover crop residues under SPR promoted microbial activity and litter decomposition (Freckman, 1986; Yahdjian et al., 2006). Conversely, the application of water below the soil surface under SDI treatments avoided soaking the litter, thus reducing microbial activity and fresh organic matter breakdown. Therefore, the higher amount of available C into the soil under SPR than under SDI may have been partly due to higher crop residue decomposition, which seems to be another important factor behind the differences in N_2O between treatments (Weier et al., 1993; Bateman and Baggs, 2005). Interestingly, the contribution of litter and litter-N decay rates to N_2O emissions differed for maize and soybean. Nitrous oxide emissions during maize were associated to (total) litter decay, whereas N_2O emissions during soybean were associated to litter N decay. This suggests that in highly N-fertilized crops (such as maize in our study), the main effect of residue decomposition on N_2O emissions is by providing a C source to denitrifiers (Weier et al., 1993), while the available N released from residue decomposition is less important because there is sufficient N in the soil for soil microorganisms from fertilization. Conversely, for unfertilized crops (such as soybean in our study), N released from litter decomposition may play a major role for N_2O emissions by providing N to nitrifiers and denitrifiers (Senbayram et al., 2019).

Nitrous oxide emissions were higher in 2020 than in 2019 for the maize treatments. This was probably a result of the higher amount of rainfall during the growing season in 2020 (+79% compared to 2019), which affected the WFPS dynamics, particularly for the SDI treatments. Indeed, the higher rainfall increased the WFPS peaks of SDI (81% for SDI70-M and 85% for SDI140-M in 2020, compared to 65% and 72% for the same treatments in 2019), thus stimulating denitrifying microorganisms' activity and therefore N_2O emissions. Further evidence for this mechanism is the strong relationship between cumulative rainfall and N_2O emissions during the growing season of maize.

4.3. Implications for sustainable and efficient management of water and N-supply

Sprinkler irrigation combined with one/two applications of N-fertilizers at a high rate is a widespread agricultural practice due to operational feasibility and reduced labor cost (Black et al., 1985; Grant et al., 2012; Xia et al., 2017). However, our results indicate that this common practice may lead to increased N losses, thus reducing N-fertilization efficiency compared with subsurface drip irrigation. The negative consequences of sprinkler irrigation may be lessen by adopting more efficient sprinkler systems (i.e. micro-sprinklers) rather than hose reel and/or by splitting N-fertilizer applications similarly to SDI management. Nevertheless, the agronomic and environmental performance of subsurface drip irrigation varied strongly depending on the crop, dripline distance and growing-season rainfall. Here we show that the benefits of subsurface drip irrigation are higher in crops with high water and N demand, such as maize, than in less demanding crops such as soybean. In addition, within subsurface drip irrigation systems, the choice of dripline distance has a determinant impact on N-fertilization efficiency and partially on yield and iWUE: a narrow dripline distance increases yield, iWUE, and NUE in maize, and this is particularly important during dry years; conversely, during wet years when the contribution of irrigation method is less crucial, dripline distance is less important.

Our results may help defining the amount of rainfall at which using micro-irrigation systems may increase NUE and yield in fine-textured soils. When around 30% of crop water requirements estimated as ETc are supplied with irrigations, SDI (regardless of dripline distance) may not provide benefits, while when the ratio is around 60%, SDI may increase yield and N-efficiency compared with sprinkler irrigation. This implies that the use of subsurface drip irrigation should be particularly promoted in semi-arid regions, where these systems are already in use. However, since in many temperate areas across the world the climate is changing rapidly towards drier summer seasons (Field et al., 2012), using micro-irrigation systems that minimize water losses through evaporation (i.e. SDI) and increase water use efficiency will become more important in a greater proportion of arable land across the world. Using less water for crop irrigation is crucial to preserve freshwater availability, but also for reducing the C footprint due to the energy required for water extraction, treatment, and distribution (Shrestha et al., 2012).

Our results support the promising outcomes of previous studies with SDI (Patel and Rajput, 2009; Maris et al., 2015; Bronson et al., 2018; Martínez-Gimeno et al., 2018; Gao et al., 2019; Valentín et al., 2020) and show that, when installing a subsurface drip irrigation system for field crops, dripline distance should be designed matching plant spacing, which was 70 cm in the present study, to increase yield performance and reduce negative environmental impacts. However, reducing dripline distance means increasing the number of driplines per hectare, thus increasing investment costs. In addition to lateral spacing, also dripline installation depth may play a major role for steering environmental, productive, and economical performances of field crops. An adequate burial depth depends on several factors, including crop type, soil texture, water source, climate, and cultural practices (Lamm et al., 2006). Thus, long-term studies conducted over several years – performed also in other pedoclimatic conditions and with different crop types – as well as focusing on the interaction between dripline spacing, depth, and installation costs are needed for extending these results at larger scale and for a complete evaluation of SDI system efficiency. These studies should also include lower N and water application rates to explore the potential of sub-optimal amounts to further increase the environmental benefits of SDI. Moreover, future experiments should also use several chambers in a gradient from the dripline to document the spatial variability of N_2O emissions with drip irrigation systems, which may be substantial (Abalos et al., 2014).

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CRediT authorship contribution statement

Federico Ardenti, Vincenzo Tabaglio and Andrea Fiorini conceived the ideas and designed the methodology; Federico Ardenti, Federico Capra, Michela Lommi and Stefania Codruta Maris collected the data; Federico Ardenti, Alessia Perego and Chiara Bertora analysed the data; Federico Ardenti, Diego Abalos and Andrea Fiorini led the writing. All authors contributed critically to the drafts and gave final approval for publication.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.fcr.2022.108732.

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