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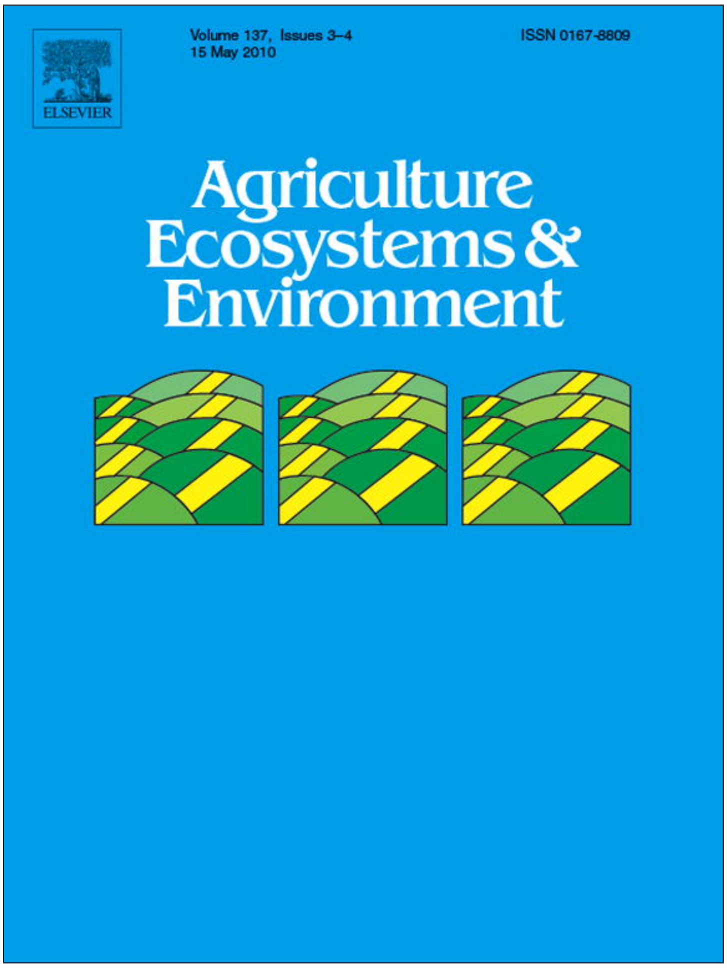

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Cover cropping affects soil N_2O and CO_2 emissions differently depending on type of irrigation

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ABSTRACT

Agricultural management practices such as subsurface drip irrigation (SDI) and winter legume cover cropping (WLCC) influence soil water dynamics as well as carbon and nitrogen cycling, potentially changing emission rates of soil CO_2 and N_2O, principal greenhouse gases. A split plot tomato field trial in California's Central Valley was used to evaluate the use of SDI and WLCC on event-based CO_2 and N_2O emissions. SDI and WLCC were compared to the region's more conventional practices: furrow irrigation (FI) and no cover crop (NCC). Our results indicate that SDI offers the potential to manage cover crops without the significant increases in greenhouse gas production during the growing season as seen under FI cover-cropped systems. The highest N_2O emissions occurred during the beginning of the rainy season in November in the FI–WLCC treatment (5 mg m^{-2} h^{-1}) and the lowest in August in the SDI–NCC treatments (4.87 μg m^{-2} h^{-1}). CO_2 emissions ranged from 200 mg m^{-2} h^{-1} during the rainy season (winter) and >500 m^{-2} h^{-1} during the growing season. Though no differences were detected in CO_2 emissions between irrigation practices, mean CO_2 emissions under WLCC were 40% and 15% greater compared to NCC under FI and SDI, respectively. The treatment with the greatest effect on CO_2 and N_2O emissions was WLCC, which increased average growing season N_2O and CO_2 emissions under FI by 60 μg N_2O m^{-2} h^{-1} and 425 mg CO_2 m^{-2} h^{-1} compared to NCC. In SDI there was no effect of a cover crop on growing season CO_2 and N_2O emissions. In the rainy season, however, SDI N_2O and CO_2 emissions were not different from FI. In the rainy season, the cover crop increased N_2O emissions in SDI only and increased CO_2 emissions only under FI. Subsurface drip shows promise in reducing overall N_2O emissions in crop rotations with legume cover crops.

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1. Introduction

Greenhouse gas (GHG) production in cultivated soils is highly dependent on the type of agricultural practice, such as fertilizer additions and irrigation and cover crop management (Mosier et al., 1998). In Mediterranean climates, such as in California, intensive irrigation and N fertilization can lead to conditions that promote elevated CO_2 and N_2O emissions (Linn and Doran, 1984). This is particularly true for flood irrigation practices such as furrow irrigation (FI) that inundate the soil profile during irrigation events. However, little information exists to contrast GHG emissions from furrow versus defined irrigation delivery systems such as subsurface drip irrigation (SDI). SDI could potentially mitigate GHG production from agricultural systems by delivering water directly to crop roots in small quantities but higher frequencies compared to the inundate/dry cycle of FI. The restricted soil-wetting pattern of SDI leaves much of the soil profile and soil surface dry in comparison to FI (Hanson et al., 2000), while keeping a water-filled pore space (WFPS) of around 20–30% in the area immediately surrounding the drip line (Hanson and May, 2007). Maintaining a lower WFPS in SDI compared to FI may limit denitrification which is tightly coupled with a WFPS > 60% (Ruser et al., 2006). Furthermore, though FI delivers water less frequently than SDI, the flooding characteristics of FI lead to severe wet–dry stresses in the soil. Wet–dry cycles in the soil profile have been shown to elevate the amplitude of CO_2 pulses as well as increase nitrification and N_2O losses (Rudaz et al., 1991; Appel, 1998; Fierer and Schimel, 2002).

The use of winter legume cover crops (WLCCs) can add a substantial amount of C to the soil, mitigating a portion of agricultural soil CO_2 emissions (Jarecki and Lal, 2003). However, this benefit can be offset by subsequent increases in N_2O production. Cover crops, particularly N-rich legumes, increase the amount of available C and N in the soil and thus, the microbial activity that drives CO_2 and N_2O emissions may no longer be substrate limited (Varco et al.,

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1987; Aulakh et al., 1991; Watson et al., 2002; Sainju et al., 2007). The use of hairy vetch as a winter cover, for example, can supply between 60 and 150 kg ha^{-1} of N (Christopher and Lal, 2007) and, if not synchronized well with the following crop's needs, could lead to an abundance of available C and an excess in soil-N, potentially enhancing denitrifier activity or nitrate leaching (Follet, 2001). The push to include winter cover crops to address winter runoff, water quality and soil sustainability issues requires further information on the interaction of cover crops with different irrigation practices and subsequent influence on seasonal GHG emissions (Rosecrance et al., 2000; Poudel et al., 2001).

Recent literature reviews on agriculture GHG emissions are largely comprised of studies on non-irrigated fields or lack comparisons of different irrigation systems within a similar context (Bouwman et al., 2002; Six et al., 2004; Novoa et al., 2006; Galbally et al., 2008). The objective of this study was to compare CO_2 and N_2O emissions under SDI to FI in a processing tomato row-crop system with and without WLCC. Tomatoes are an ideal crop for this field study because they are the third highest row-crop commodity in California, which produces 95% of U.S. processing tomatoes (California Department of Food and Agriculture, 2009) and the use of SDI in processing tomatoes is increasing rapidly (Coatney, 2009). We hypothesized that the soil-wetting pattern under SDI would decrease CO_2 and N_2O emissions in comparison to FI and that the use of WLCC would impact GHG emissions differently depending on the type of irrigation used. Under SDI, the reduced availability of mineral N through fertigation (small increments of fertilizer delivered directly to the crop roots through the drip tape) was considered to further reduce GHG production rates compared to a single fertilizer application under FI. Seasonal differences and field-level spatial heterogeneity were expected under both FI and SDI based on irrigation wetting patterns and seasonal temperature changes.

2. Materials and methods

2.1. Site description

The field experimental plots were initiated in 2003 at the Russell Ranch Sustainable Agricultural Research Facility on the University of California, Davis campus (32°N, 121°50′W). Field data collection began the following spring 2006. The region has a semi-arid Mediterranean climate with an average annual precipitation of 480 mm, where most of the rainfall is between October and April. Average growing season (May through September) temperatures are typically 21 °C with the rest of the year (October through April) averaging 12 °C (California Irrigation Management Information System, Station No. 6, Davis, CA) (Fig. 1). The soils at the site are classified as Reiff loam (coarse-loamy) and Yolo silt loam (fine-silty), nonacid, thermic Mollic Xerofluvents. Processing tomatoes (*Lycopersicon esculentum* L., Var. 3155) were grown during the growing season as well as the 3 years prior to data collection.

2.2. Field treatments

Field treatments were set up as a randomized split plot design with subsurface drip irrigation (SDI) and furrow irrigation (FI) as the main plot treatments. Subplot treatments were winter legume cover crop (WLCC) and no winter legume cover crop (NCC). Each plot was 0.15 ha with 4 replications. The WLCC treatments were seeded at a 1:3 mass ratio of hairy vetch (*Vicia villosa* Roth) and Australian winter pea (*Lathyrus hirstutus* L.). In 2006, the cover crop was flail mowed on April 29th and then mulched and incorporated on May 9th. Tomatoes were transplanted on May 19th. The beds were on 1.52 m spacing (center-to-center) and tillage practices were typical to the area (i.e. subsoiling, disking, landplaning, and bed listing).

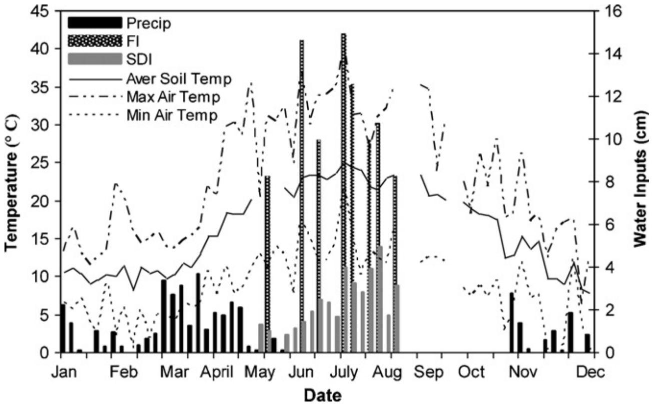

Fig. 1. Minimum, maximum daily air temperature, average daily soil temperature, daily precipitation (SO: CIMIS database; Davis Station) from January 1st to December 31st 2006 and furrow irrigation (FI) and subsurface drip irrigation (SDI) irrigation events in cm of water applied per event.

2.3. Irrigation

The drip tape in the SDI plots was installed when the study was established in 2003 to a depth of 25.4 cm in the center of each bed. The drip tape was Queen Gil-medium flow, 6 mm in diameter with 10.16 cm emitter spacing (Queen Gil International, Israel). A flow rate of 4 L m^{-2} h^{-1} was maintained at a pressure of 69 kp during irrigation events. Two removable pressure gauges were used to monitor pressure uniformity and to identify leaks in the drip tape. Irrigation events for both SDI and FI were scheduled based on the ET replacement method efficiencies described by Hanson et al. (1999) and physical inspection by the frequent monitoring of soil water contents to a 12-cm depth using a Hydrosense time domain reflectrometer probe (Campbell Scientific, Edmonton, Alberta). ET data were downloaded every 1–3 days from the California Irrigation Management Information System (CIMIS) website (http://wwwcimis.water.ca.gov/cimis/welcome.jsp). Irrigation events under FI were typically every 6–10 days, whereas SDI events were every 2–4 days. Water inputs to the field for FI and SDI were monitored using in-pipe water gauges at the SDI pump manifold and the first in-flow gated pipe for FI. Water inputs from precipitation events were collected from the CIMIS database.

2.4. Fertilization

On May 12th 2006, 50.4 kg ha^{-1} of 15–15–15 NPK was side dressed to a 20-cm depth in all treatments on both side of the beds. On June 12th 2006 all FI plots received an additional split-shank NH_4SO_4 (20% N) fertilizer application at a rate of 112 kg N ha^{-1}. The SDI plots were fertigated over the course of the growing seasons with the first fertigation event beginning on June 16th 2006. Each application was approximately 8.6 kg N ha^{-1}, totaling 13 fertigation events and 112 kg N ha^{-1} over the entire season. Fertigation events were determined based on tomato crop-N requirements throughout the season. Though the fertilization practices of SDI and FI differed in timing, they reflect typical grower practices and application rates were matched to reflect the same total N input.

2.5. Soil sampling and analyses

Soil samples were taken throughout the course of the experiment for total C and N and inorganic N. Sampling frequency

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was about every 3 weeks during the period of tomato establishment to just before senescence. Sampling frequency in the winter was concentrated around periods of rapid cover crop biomass increases and following cover crop incorporation. Soil samples were taken from a depth of 0–15 and 15–30 cm using a 2.54-cm diameter hammer corer. For soil inorganic N concentrations, a soil sub-sample was passed through a 2-mm screen followed by an extraction of 30 g field-moist soil with 100 mL of a 1 M KCl solution. Inorganic NH_4^+ and NO_3^- concentrations were determined colorimetrically (Foster, 1995; Doane and Horwath, 2003) using a UV–vis spectrophotometer (UV Mini 1240; Shimadzu, Kyoto, Japan). Gravimetric soil water contents were determined on 105 °C oven-dried soils. Total soil C and N was determined on a NA 1500 continuous flow combustion C and N analyzer (Carlo-Erba, Thermo Instruments; San Jose, CA).

Soil samples for bulk density were taken on April 2007, using a hydraulic sampler (Giddings, Windsor, CO) from which four soil cores from each treatment plot were taken to a 60-cm depth from the middle of the plant row. The 60-cm cores were processed for bulk density at 5-cm intervals up to 15 cm and then 15-cm intervals up to the 60-cm depth.

2.6. CO_2 and N_2O sampling and estimations

Measurements of soil CO_2 and N_2O began January 2006. Gas measurements were taken from three zones (the plant line, shoulder of the bed, and furrow) within each treatment, with one sampling chamber per zone, in order to capture spatial variability across the soil beds due to irrigation and field management. A weighted average of the three sampling zones was used to estimate total crop-bed emissions for each sampling date.

Soil CO_2 emissions were measured with an automated portable infra-red gas analyzer (LI-COR, model LI8100, Lincoln NE). The automated chamber was placed over 10-cm PVC collars, inserted into the soil to a depth of 4 cm at which point CO_2 concentrations in the headspace were measured automatically every 10 s over a 5-min deployment period. Areas around the soil collars were kept clear of vegetation and soil collars were only moved during field operations or when chamber placement appeared to be affecting soil environment conditions (i.e. flooding, shading). CO_2 emissions ($mg\,CO_2\,m^{-2}\,h^{-1}$) were calculated with LI-COR software from either a linear or exponential model.

N_2O sampling was carried out on the same day as CO_2 sampling by fitting vented PVC chambers (10 cm ht. 10.2 cm dia.) on the same collars used for CO_2 measurements (Hutchinson and Mosier, 1981). At 20, 40, and 60 min after deployment 12 mL air samples were taken from the chambers and immediately injected into evacuated gas-tight, 6 mL glass vials (Labco Exetainers, UK). Several air blanks were taken throughout the course of each N_2O sampling event and subsequently used as N_2O concentrations for time zero. Samples of a known N_2O concentration were also taken at each N_2O sampling for quality control. The sample and standard N_2O concentrations were determined on a gas chromatograph with an electron capture detector (Hewlett Packard 6890; Wilmington, DE). The rate of N_2O emissions was calculated from the change in concentrations (ppm) h^{-1} using an exponential model (Hutchinson and Mosier, 1981).

Emissions of CO_2 and N_2O were measured throughout the growing season every 10 days with greater frequency around fertilization and tillage events. Emission measurements were scheduled so that half of the sampling events occurred immediately before and half immediately following (1–2 days) furrow irrigations events to capture both dry and wet field conditions. SDI emissions were monitored on the same schedule as FI. Since irrigation occurred every 2–3 days under SDI it was assumed that we would be able to capture both pre and post-SDI irrigation events based on the above FI schedule. During the rainy season, (post-harvest to planting) gas measurements were taken every 2–3 weeks as recommended by Parkin and Kaspar (2004) or following large rain events. Gas sampling events were infrequent during the period between post-harvest and the onset of the rainy season (September through early November) as N_2O chamber concentrations were below analyzer detection limits; possibly due to the drier and cooler soil conditions.

To limit any significant diurnal temperature influences, all N_2O measurements were taken in the mid morning when the average difference between the maximum and minimum air temperature was no more than 3–7 °C (Crill et al., 2000; Smith and Dobbie, 2001; Parkin and Kaspar, 2004). However, CO_2 gas measurements spanned a longer time period, from early morning to mid afternoon (0800–1400 h), due to sampling equipment and number of sampling sites. To account for diurnal temperature variation and estimate daily average emission rates, the Q_{10} function was used. The calculated Q_{10} value is a unit less coefficient that describes the magnitude of change in soil respiration rates based on a 10 °C change in temperature and is thus used to estimate how soil respiration rates change in response to a change in temperature (Janssens and Pilegaard, 2003). From this, the coefficient can be applied to single short-term observations to extrapolate daily respiration rates.

Six diurnal CO_2 sampling events for all treatments were used in determining Q_{10} values, three of which occurred during the growing season and three in late fall and spring. From these diurnal CO_2 sampling events, six different Q_{10} functions were determined to represent time periods with similar air temperature and soil–moisture ranges, and ranged from 1.5 to 2.8.

2.7. Soil moisture and soil temperature

At the time of each gas sampling event, soil temperature and soil moisture were measured at three different points close to each permanent PVC collars. Soil temperature was taken at 6 and 12-cm depths and soil moisture was determined using a TDR (described above). The TDR values were converted to percent water-filled pore space (WFPS) using known bulk density and a particle density of $2.65\,g\,cm^{-3}$ for obtaining pore volume. Air temperature was also taken three to four times for every gas sampling event during the duration of the sampling period.

2.8. Statistical analysis

A split plot design was used to assess main effects of treatments and treatment interactions. N_2O emission values were log transformed before ANOVA analysis (SAS Institute Inc.; North Carolina, United States) based on the results from Wilks–Shapiro test for normality and back-transformed for reporting results. An AIC test statistic was used to test for Goodness-of-Fit. Least square means with a Tukey–Kramer test ($P < 0.05$) were used to identify significant differences among treatment means. In order to compare treatments over seasons, a second split plot ANOVA was run where "sampling date" was removed from the model and replaced by "season", where sampling dates were grouped according to "rainy season" or "growing season". A stepwise multiple regression analysis was performed with a maximum R^2 improvement procedure which uses forward selection to fit the best one-variable model, the best two-variable model, and so on, in order to maximize R^2. The first regression used CO_2 as the response variable against soil moisture, soil temperature and N_2O and was then repeated using N_2O as the response variable and CO_2 and a predictor variable. These variables were then checked for significant correlations using Pearson's correlation coefficient.

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3. Results

3.1. Soil characteristics and cover crop C and N input

Total soil C and N did not change significantly under the different irrigation treatments (data not shown). However, WLCC had a significant positive effect ($P < 0.001$) on the average soil C content regardless of irrigation treatment. Soil C for the top 0–15 cm ranged from 1.1% for soils with no cover crop to 1.3% for soil with a cover crop. Total soil-N was not affected by cover crop and averaged 0.1% across all treatments. Soil bulk density was similar across all treatments with a mean of 1.27 g soil cm^{-3} from 0 to 15 cm.

The cover crop mix of hairy vetch and Australian winter pea had a C:N of 11 and added a mean 107 kg biomass-N ha^{-1} and 1.5 t biomass-C ha^{-1} to the WLCC treatments annually.

3.2. Water use efficiency

The water use efficiency of both FI and SDI was calculated based on crop yield per unit of water input for both systems. The tomato crop yields averaged 79 t ha^{-1} and did not vary significantly between irrigation treatments. Water inputs via irrigation were significantly different between SDI and FI, where 38.12 cm of water was applied to SDI during the growing season compared to 88.64 cm under FI (Fig. 1). In addition to the amount of irrigation water applied for SDI and FI, Fig. 1 shows the frequency of irrigation events with FI amounting to 8 total events averaging 8–10 cm of water applied per event while SDI had 12 different irrigation events at about 2–4 cm of water applied per event. Based on the above data, SDI was estimated to have over 100% higher water use efficiency compared to that of FI.

3.3. Soil moisture and temperature

Fig. 2 shows the weighted average of WFPS values from each sampling zone across the crop bed (furrow, bed shoulder, and plant line) for each treatment. The WFPS for SDI remained relatively steady between 20% and 30% during the growing season (May through September) compared to 40–60% under FI. ANOVA results showed that irrigation and season had a significant effect on WFPS ($P < 0.001$) with FI being higher than SDI during the growing season regardless of cover crop ($P < 0.05$). Rainy season WFPS values for FI were similar to those FI values obtained during the growing season. In the SDI systems, soil moisture was significantly higher in the rainy season compared to the growing season. When split by season, SDI and FI WFPS were similar to each other in the rainy season (47% and 48%, respectively), though SDI remained lower (20%) than FI (48%) in the summer ($P < 0.05$).

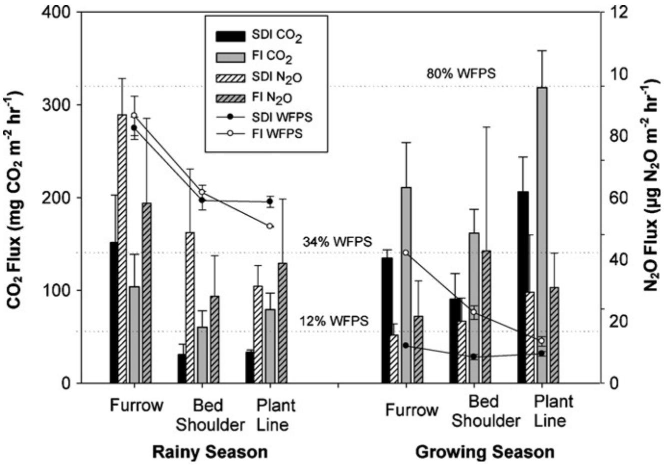

Fig. 3. Spatial distribution of soil N_2O and CO_2 emissions and soil water-filled pore space (% WFPS) to a 12-cm depth. Measurements were taken February 15th and August 4th 2006 from the furrow, shoulder of the bed, and plant line for both subsurface drip irrigation (SDI) and furrow irrigation (FI) treatments. Data are mean ± SE ($n = 3$).

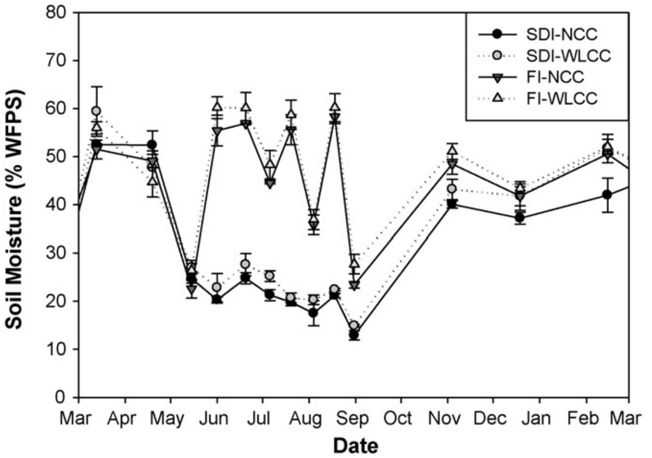

Fig. 2. Percent water-filled pore space (WFPS) for a 12-cm profile under subsurface drip irrigation (SDI) and furrow irrigation (FI) by winter legume cover crop (WLCC) and no cover crop (NCC) from March 2006 to March 2007. Data are mean ± SE ($n = 3$).

We expected soil moisture to vary across the crop bed based on irrigation wetting patterns during the growing season and to be uniform during the winter. In FI, higher WFPS was observed across the entire width of the bed compared to SDI, with the highest WFPS values in the furrow zone during the growing season as anticipated (Fig. 3). Contrary to what was expected, SDI WFPS in the furrow zone was statistically higher (mean WFPS 22%) than all other SDI zones during the growing season, with the plant line and shoulder bed being the driest (mean 17% and 11% WFPS). The highest growing season WFPS values were observed under FI in the furrow zone (>60%), often reaching over 80% WFPS following irrigation events.During the rainy season, WFPS was only statistically different between SDI and FI in the plant line zone ($P < 0.05$). Both SDI and FI exhibited significantly higher WFPS (>50%) in the furrow zone during the rainy season compared to the bed shoulder zone and plant line ($P < 0.05$).

Though there were no treatment effects on soil temperature, the season (rainy season and growing season) had a significant effect ($f = 912.88$, $P < 0.005$) with a mean soil temperature of 25.4 and 10 °C in the growing season and rainy season, respectively (Fig. 1).

3.4. Soil nitrate

Soil NO_3^- levels followed a common trend for all treatments, except in SDI–NCC, where NO_3^- started off low during the spring and continued to increase until mid-way through the growing season at which point NO_3^- levels began to decline in all treatments (Fig. 4). The highest NO_3^- concentrations occurred under FI–WLCC (60–75 µg g soil^{-1}) in July, 2.5 weeks following FI fertilization, followed by the August and then September sampling dates (Fig. 4). NO_3^- levels had dropped in all treatments to <5 µg by February. During peak soil NO_3^- concentrations, the FI treatments were two to three times greater in soil NO_3^- than the SDI treatments ($P < 0.01$). However, during the rainy season, (spring and winter months) SDI and FI NO_3^- were similar regardless of cover. For all sampling dates, except December and February, both the FI and SDI treatments exhibited significant differences in NO_3^- between NCC and WLCC, where WLCC NO_3^- was often 10–20 µg higher compared to NCC ($P < 0.001$) during growing season months. SDI–NCC

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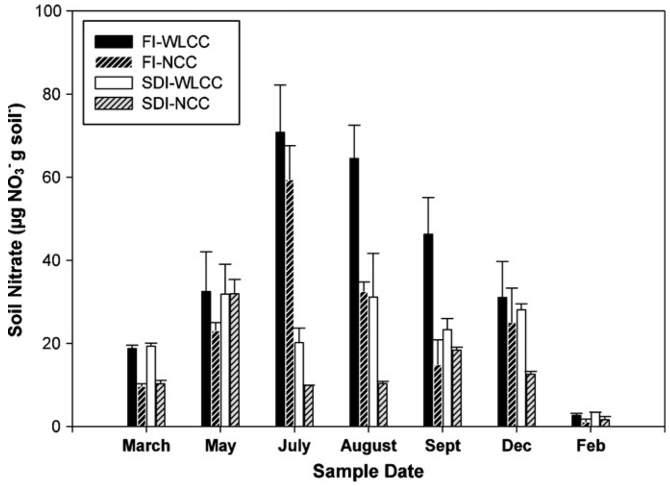

Fig. 4. Soil NO_3^- concentrations from 0 to 15 cm. Treatments are furrow irrigation (FI), subsurface drip irrigation (SDI), winter legume cover crop (WLCC), and no cover crop (NCC). Data are mean ± SE ($n = 3$).

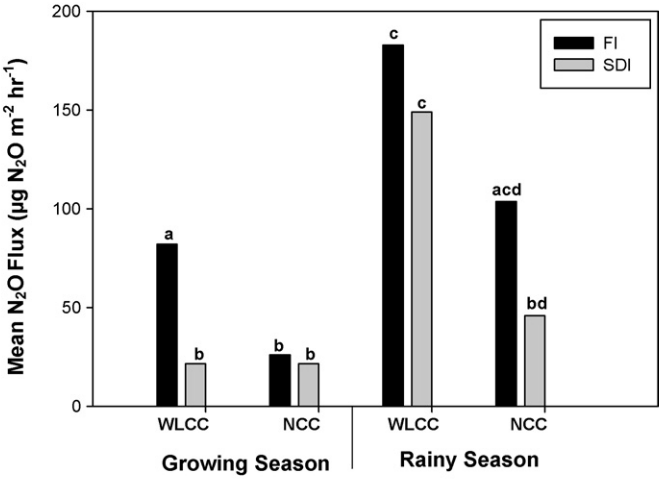

Fig. 5. Least square means of N_2O emissions of furrow irrigation (FI) and subsurface drip irrigation (SDI) during the growing and rainy season with winter legume cover crop (WLCC) and with no cover crop (NCC). Means with different letters differ ($P < 0.05$).

consistently exhibited the lowest NO_3^- for all but two of the sampling dates.

3.5. N_2O emissions

Soil temperature, irrigation events and WLCC had the greatest influence N_2O emission (Table 1). Soil moisture was positively correlated to N_2O emissions, explaining 22% of the variation in N_2O emission rates. ANOVA test results indicate the cover crop treatment had the greatest effect on N_2O ($f = 24.8$, $P < 0.001$) emissions followed by irrigation ($f = 19.37$, $P < 0.001$), where SDI decreased N_2O emissions by half, compared to FI, regardless of WLCC.

3.5.1. Growing season

Growing season treatment mean N_2O emissions are shown in Fig. 5. SDI mean N_2O emissions were only significantly lower than FI when combined with WLCC. The interaction of FI with WLCC increased mean N_2O emissions by approximately 60 µg $N_2O\ m^{-2}\ h^{-1}$ during the growing season compared to the FI–NCC treatment. However, there was no significant interaction between SDI and WLCC, where SDI combined with WLCC resulted in no change in N_2O emission compared to SDI–NCC (Fig. 5).

N_2O emissions were variable during the growing season, ranging from as low as 0 and up to almost 400 µg $N_2O\ m^{-2}\ h^{-1}$ (Fig. 6). Differences between treatments in N_2O emissions varied significantly by sampling date and are presented in Fig. 6. Under SDI, N_2O emission rates were relatively low (<50 µg $N_2O\ m^{2-}\ h^{-1}$) and consistent between sampling dates compared to FI. N_2O emissions were different between SDI and FI for all sampling dates, with SDI showing lower emissions compared to FI. The FI–WLCC treatment had the largest peak amplitude between sampling dates, and often the highest rates of emissions compared to all other treatments. No significant differences occurred in N_2O emissions relative to crop bed location (Fig. 3).

Table 1
Correlation matrix (*r* values) among the measured variables.

Variable	CO_2 (mg $m^{-2}\ h^{-1}$)	N_2O (µ $m^{-2}\ h^{-1}$)	Soil moisture (% WFPS)
N_2O (µ $m^{-2}\ h^{-1}$)	0.05788		
Soil moisture (% WFPS)	−0.24***	0.22***	
Soil temp (°C)	0.45***	−0.052	−0.53***

Soil moisture (percent water-filled pore space, WFPS) to a 12-cm depth; soil temperature at a 6-cm depth.
*** Significant at $P < 0.001$.

3.5.2. Rainy season

Average rainy season N_2O rates under SDI were not significantly different than FI. Under SDI–WLCC, mean N_2O emissions significantly increased by three times as much compared to the growing season (Fig. 5). Furthermore, differences within SDI between WLCC and NCC occurred where WLCC had a mean N_2O emission rate three times greater than that of NCC. This interaction between SDI and WLCC was not present during the growing season. FI–WLCC

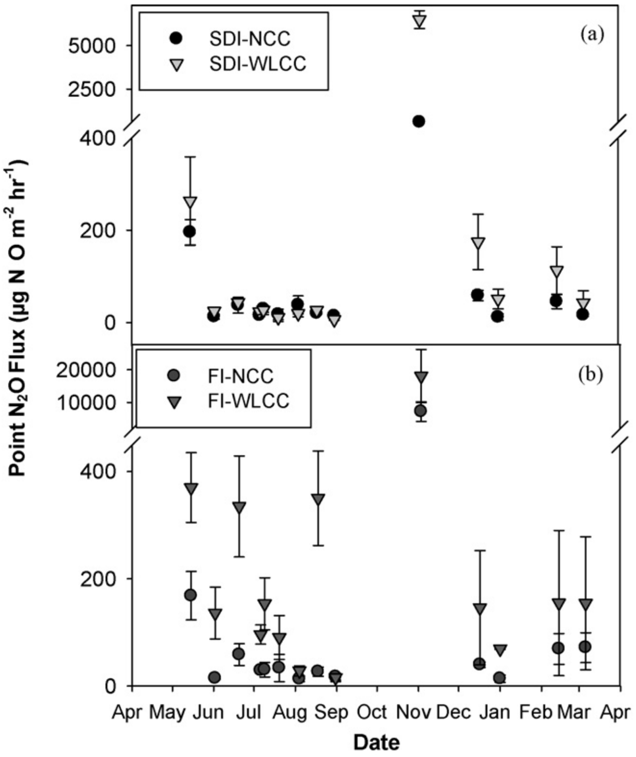

Fig. 6. (a and b) Point N_2O emissions from January 2006 to December 2006. Treatments are furrow irrigation (FI), subsurface drip irrigation (SDI), winter legume cover crop (WLCC), and no cover crop (NCC). Data are mean ± SE ($n = 3$).

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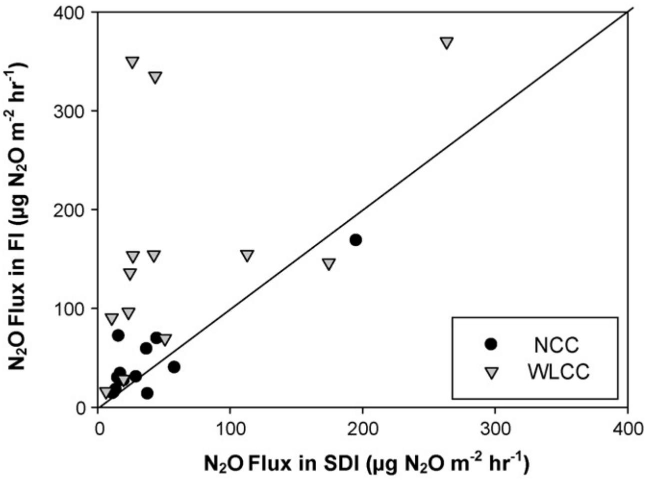

Fig. 7. Relationship of point N_2O emissions between furrow irrigation (FI) and subsurface drip irrigation (SDI) with winter legume cover crop (WLCC) or with no cover crop (NCC).

also had higher mean N_2O emissions compared to NCC. The lowest rainy season means N_2O emission was under SDI–NCC and the rates from individual sampling dates did not differ significantly from growing season N_2O sampling dates under SDI–NCC (Fig. 6). Exceptionally high emissions were recorded on November 4th, 2006 (upwards of ~5 mg N_2O m^{-2} h^{-1}) after the season's first significant rainfall (Fig. 6). To verify the high emissions, a second sub-sampling occurred on November 5th and although N_2O rates had already begun to drop, emissions remained high compared to season averages (data not shown).

The rainy season spatial characteristics of N_2O emissions in the two irrigation treatments were different from those exhibited during the growing season. Fig. 3 is a characteristic example of the spatial distribution of N_2O emissions between seasons, with highest N_2O emissions appearing in the furrow zone for both SDI and FI in the rainy season.

3.5.3. *Summary treatment effect on N_2O point emissions*

Figs. 7 and 8 are summary treatment comparisons from all sampling dates for N_2O. Fig. 7 compares N_2O point emissions under FI to SDI, with cover crop as the sub treatment. More than 75% of measured emissions are above or at the 1:1 line, indicating that FI N_2O emissions were most often either greater or similar compared to SDI. It can be further concluded, that of the 18 measurements above 100 μg m^{-2} h^{-1}, all but 1 are from the WLCC treatments.

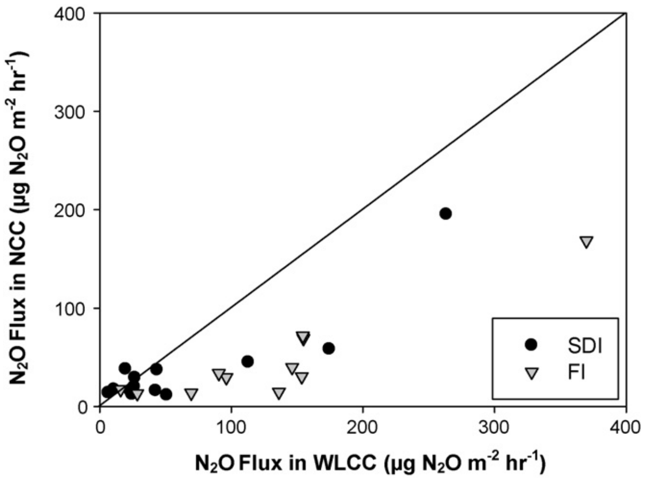

Fig. 8. Relationship of point N_2O emissions between winter legume cover crop (WLCC) and no cover crop (NCC) with furrow irrigation (FI) or with subsurface drip irrigation (SDI).

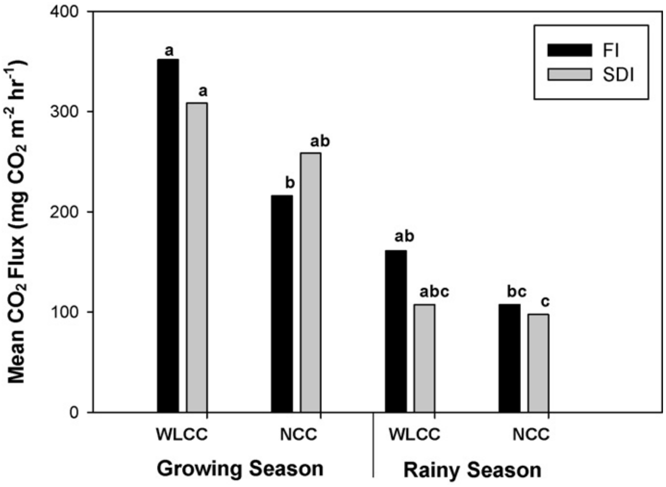

Fig. 9. Least square means of CO_2 emissions of furrow irrigation (FI) and subsurface drip irrigation (SDI) during the growing and rainy season with winter legume cover crop (WLCC) and with no cover crop (NCC). Means with different letters differ ($P < 0.05$).

Fig. 8 shows cover crop treatment N_2O emissions with irrigation as the subtreatment. Though most of the emission measurements are clustered under 100 μg m^{-2} h^{-1}, FI makes up more than 60% of those emissions above 100 μg m^{-2} h^{-1}. Only a few N_2O emission measurements sit above the 1:1 line, indicating that the WLCC treatments were generally greater than the NCC treatment measurements for any given sampling date. Moreover, all of the measurements above 100 μg m^{-2} h^{-1} are in the WLCC treatment, with the exception of one NCC measurement that is around 200 μg N_2O m^{-2} h^{-1} from the SDI treatment.

3.6. *CO_2 emissions*

Similar to N_2O emissions, soil temperature, irrigation event, and WLCC had the most influence on CO_2 emissions. Soil temperature had the strongest positive correlation to CO_2, accounting for 45% of the variation in emission rates (Table 1). Soil moisture was negatively correlated with CO_2 emissions. ANOVA results indicate that the cover crop treatment had the greatest effect on CO_2 emissions ($f = 72.4$, $P < 0.001$). There was also a significant seasonality effect for CO_2 ($P < 0.05$).

3.6.1. *Growing season*

In comparing SDI to FI, mean CO_2 emissions were statistically similar (Fig. 9). Analogous to the effect of WLCC on N_2O rates, mean CO_2 emissions under FI were also higher as a result of the cover crop (Fig. 9), though this was only true under FI. Under SDI there was no difference in mean CO_2 emissions when WLCC was compared to NCC. Emissions for CO_2 ranged from <200 to > 500 mg CO_2 m^{-2} h^{-1} though values greater than 400 mg CO_2 m^{-2} h^{-1} were less common (Fig. 10) and were generally observed in the FI treatments following fertilization and tillage events. CO_2 emissions increased steadily over the course of the growing season, peaking in both FI and SDI treatments in mid-July (Fig. 10). For most sampling dates, there were no differences in CO_2 emissions between SDI and FI. The FI systems had slightly more variability in emission rates from one sampling date to the next as well as the greatest differences between cover crop treatments. CO_2 emissions were higher in FI–WLCC compared to NCC for 7 of the 8 sampling dates. In SDI only the first two sampling dates (May and June) showed

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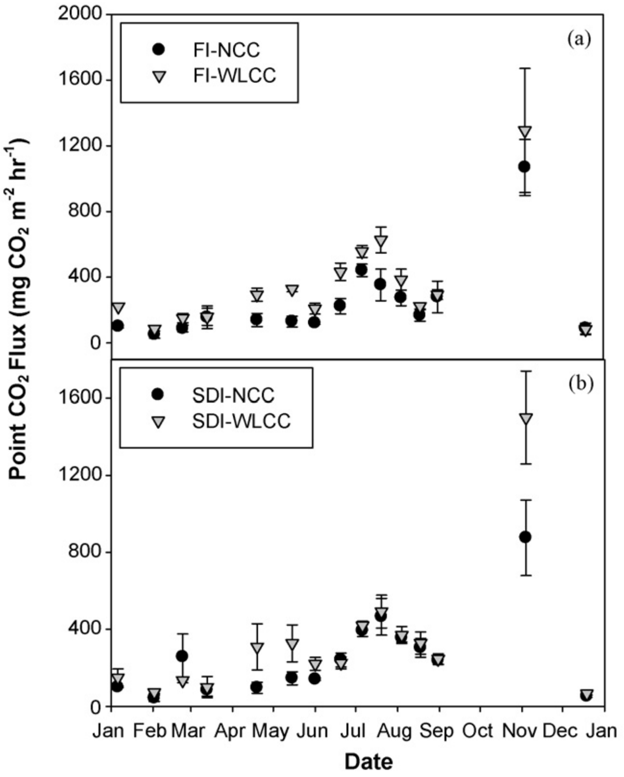

Fig. 10. (a and b) Point CO_2 emissions from May 2006 to March 2007. Treatments are furrow irrigation (FI), subsurface drip irrigation (SDI), winter legume cover crop (WLCC), and no cover crop (NCC). Data are mean ± SE ($n = 3$).

any difference between WLCC and NCC (Fig. 10). Both the SDI and FI treatments had the highest CO_2 and emission rates in the plant line, followed by the furrow zone (Fig. 3) during the growing season.

3.6.2. *Rainy season*

Mean CO_2 emissions only differed when compared across treatments with FI–WLCC being significantly higher than SDI–NCC (Fig. 9). All other mean CO_2 rates between and within treatments were similar. In the rainy season, CO_2 emissions were most often <200 mg CO_2 m^{-2} h^{-1}. Though, rates for November following the season's first rain exceeded normal gas sampling emission ranges for this study (1500 mg CO_2 m^{-2} h^{-1}) (Fig. 10) as they did for N_2O for this same date. CO_2 emission rates for both SDI and FI were generally lower than those from the growing season. However, the SDI rainy season emissions for individual sampling dates were often similar or greater to FI and also exhibited far more variability between treatments and sampling dates than what was observed under SDI during the growing season (Fig. 10).

The WLCC treatment affected CO_2 rainy season values, with at least 60% of all sampling dates having highest emission rates under WLCC for both SDI and FI. This was especially true in the spring, when the cover crop had reached full canopy.

As was the case with the N_2O spatial distribution of emissions during the rainy season, the CO_2 emissions were highest in the furrow zone for both SDI and FI (Fig. 3).

4. Discussion

4.1. *Irrigation effects*

Our results for N_2O and CO_2 emissions fall within reported ranges for irrigated row-crop field experiments under similar climates (Venterea and Rolston, 2000; Burger et al., 2005; Lee et al., 2009;). For example, Lee et al. (2009) measured CO_2 and N_2O in the California Central Valley under furrow irrigation with results of 70–800 mg CO_2 m^{-2} h^{-1} and 0 to a high of 155 μg N_2O m^{-2} h^{-1}. Under similar field conditions as our study, observations by Burger et al. (2005) in a tomato system following fertilization and FI irrigation events showed similarly high rates of N_2O (>1400 μg N_2O m^{-2} h^{-1}) compared to our peak November N_2O results.

Temperature and moisture have been shown to have the greatest effect on soil respiration (Rochette et al., 1991; Lloyd and Taylor, 1994), while moisture and available soil-N and C are the two principal variables controlling N_2O production (Firestone, 1982). Our regression and correlation analysis showed that increasing soil temperature had the strongest effect on CO_2 and N_2O emissions. However, the soil temperature variable only accounted for 45% of the variation in emission rates. The negative correlation of soil moisture to CO_2 may be explained by the highest CO_2 emissions occurring during the growing season when soil moisture levels were much lower in both irrigation systems compared to the rainy season. The higher CO_2 growing season emissions, compared to the rainy season, are not only a probable artifact of additional respiration from the tomato roots but also the higher soil temperatures during the growing season (Fig. 1). The confounding temperature factor has been shown to sometimes override the influence of soil moisture on emissions when moisture is not limiting (Davidson et al., 1998).

In contrast to CO_2 emissions, N_2O was positively correlated to soil moisture. Much research has shown that the rate of N_2O emissions increases with increasing soil moisture (e.g. Dobbie et al., 1999; Abbasi and Adams, 2000; Akiyama et al., 2004) typically reaching maximum N_2O production rates after a WFPS threshold has been reached, usually between 60% and 75% (Linn and Doran, 1984). The overall low (20–30%) WFPS under the SDI treatments suggests that any N_2O emissions during the growing season could have been a product of nitrification rather than denitrification, since denitrification is generally restricted to anaerobic conditions or a WFPS above 60% (Bollman and Conrad, 1998). Studies on SDI technology indicate that WFPS only exceeds 60% within a few cm directly around the drip tape (Ayars et al., 1999; Hanson and May, 2007). Moreover, if the area immediately around the drip tape is kept at a steady WFPS > 80%, as some reports indicate (Camp, 1998; Hanson et al., 2000; Singandhupe et al., 2003), the N_2O product ratio may be lower, where more of the N_2O produced in the soil is reduced to N_2 (Robertson, 2000). Above 80% WFPS, N_2O is more efficiently reduced to N_2, as the mass flow of N_2O is reduced due to higher tortuosity of the gas pathway at this soil moisture level (Weier et al., 1993). This, in addition to the moisture-limited conditions near the soil surface under SDI, may have contributed to the generally lower growing season N_2O emissions seen under SDI compared to FI. Under FI, near saturation conditions were present in our study in the furrow zone of the bed, yet these periods were short-lived as WFPS dropped to 60–70% 48 h after an irrigation event was completed, creating ideal conditions for N_2O production under denitrification.

4.2. *Seasonal effects*

The trend of steady but low N_2O emission rates under SDI and variable N_2O rates under FI between sampling dates during the growing season is analogous to the trend in the amount of irrigation applied under SDI and FI (Fig. 1). Under SDI, each irrigation event had a similar amount of water applied; keeping soil moisture steady and moderate, whereas the amount of water applied under FI varied from one irrigation event to the next, with long periods in between irrigation events, resulting in distinct wet–dry cycles. The change from a relatively steady to a more erratic gas production rate in

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the rainy season under SDI may again be due in part to irregular water inputs via precipitation events and thus large changes in soil moisture (Figs. 1 and 3).

Another plausible explanation for the lower growing season SDI N_2O emissions may be the fertilization regime, where the N supply was applied in small but frequent amounts throughout the growing season, thus limiting the amount of residual soil-N accumulation. However, small peaks in N_2O did occur under SDI over the course of the growing season and may be a consequence of cover crop-N mineralization, as these peaks were more significantly associated with WLCC than with NCC. These small inputs of inorganic N to the SDI system via fertigation likely results in greater crop-N use efficiency, as the applications were designed to synchronize fertilizer rates with crop-N demands over the course of the season. This type of fertilizer management has frequently been shown to reduce soil NO_3^- accumulation (Smith et al., 1991; Lamm and Trooien, 2003; Zotarelli et al., 2008) and subsequently the potential for lower denitrification rates. In our study, for example soil NO_3^- was significantly lower under SDI compared to FI, where the fertilizer was applied as a single application a few weeks following tomato transplant.

The accumulation of labile organic matter and inorganic N that was potentially unutilized at the soil surface during the moisture-limited conditions of the growing season may explain the increased CO_2 and N_2O emissions observed during the rainy season in SDI. Though the FI system experienced extreme wet/dry cycles during the growing season, potentially inducing the higher FI emission rates, the SDI system had its own, yet much longer, wet/dry cycle based on seasonal wetting patterns. During the growing season the furrow zones under SDI were wet below the soil surface, yet the soil surface remained extremely dry, thus creating a condition for large soil surface CO_2 pulses following wetting in the rainy season. These data suggest that the rainy season has a significant effect in the SDI systems in producing CO_2 and N_2O. Not only is there enhanced microbial activity and turnover following rewetting after dry periods, but also C protected in soil aggregates may be released by the disruption of soil from water infiltration (Fierer and Schimel, 2002). An increase in organic C under wet–dry cycles in the soil has been shown in both field and laboratory studies (Orchard and Cook, 1983; Davidson et al., 2000; Ruser et al., 2006). Such pulses have also been observed when soil-wetting is combined with large supplies of C and N (Scheer et al., 2008; Lee et al., 2004; Hao et al., 2001). For example, Scheer et al. (2008) described a large N_2O pulse ($3000\,\mu g\,N_2O\text{-}N\,m^{-2}\,h^{-1}$) in a field planted in irrigated cotton under arid conditions, which occurred immediately following an increase in WFPS from 25% to 85% and a fertilizer application of 87.5 kg ammonium nitrate and was reported to account for 80–95% of total N_2O emissions from their study.

The exceptionally high emission rates captured on November 4th for both CO_2 and N_2O is likely a result of the influence of residual fertilizer N and the accumulation of mineralized soil-N following post-harvest and the first significant winter rainfall event. N_2O emissions under SDI from November 4th were as high as $6\,mg\,N_2O\,m^{-2}\,h^{-1}$, whereas all other sampling dates had emissions less than $0.5\,mg\,N_2O\,m^{-2}\,h^{-1}$. Similar to our November observations, Venterea and Rolston (2000) also recorded large N_2O peaks ($5\text{–}6\,mg\,N_2O\,m^{-2}\,h^{-1}$) in a California Central Valley irrigated and fertilized tomato field, though N_2O rates exceeding $2\,mg\,m^{-2}\,h^{-1}$ are generally rare and some of the highest recorded N_2O measurements in agriculture (Matson et al., 1998). These exceptionally higher CO_2 and N_2O pulses were taken 2 days following the first substantial winter season rainfall (2.74 cm) when the air temperature was relatively warm (22° C) and the tomato residue had been mulched and incorporated into the soil 1-week prior. The November 4th CO_2 and N_2O pulses were much high under the SDI systems than under the FI systems and could thus lead to cumulative emissions also being greater under SDI compared to FI, despite lower SDI emissions relative to FI for the majority of the sampling dates. Evidence for such high GHG pulses from the soil support the need for frequent sampling in order to accurately estimate total system GHG emissions. For instance, Parkin and Kaspar (2006) found that 49% of the cumulative N_2O emissions from fertilized corn plots came from just two separate sampling dates.

In this study, we did not attempt to compare cumulative emissions among treatments due to relatively the number of sampling dates, though it is arguable that key pulses were missed over the course of sampling and, thus would not be represented for mean emission rates presented in Figs. 5 and 9. However, a 2-week sampling interval during the growing season, as was used in this study, is adequate for making event-based comparisons, especially when sampling is weighted around events likely to increase emissions, such as fertilization, heavy rainfalls, and tillage. It should be considered, however, that a second year of data would provide more insight into the high November CO_2 and N_2O pulses that we reported and might also help to further explain the large increase from growing season to winter season SDI N_2O emissions.

4.3. *Winter cover crop effects*

Both the SDI and FI systems showed higher N_2O emissions when combined with WLCC, though this is only true for SDI during the rainy season and not the growing season. Using a winter cover crop can often have the benefit of taking up residual soil-N that would otherwise be leached from the system or be denitrified (Jackson et al., 1993). It also adds additional C and N via plant biomass as well as biologically fixed N that leads to increased nitrification potential and CO_2 and N_2O emissions (Verma et al., 2006). For example, in this study, December NO_3^- levels in WLCC were much greater compared to NCC (Fig. 4), likely due to cover crop N_2 fixation. Biologically fixed N from legume cover crops average about $100\,kg\,N\,ha^{-1}$ in this region (Poudel et al., 2001). Following the mineralization of cover crop-N, soil NO_3^- may increase substantially. Eblehar et al. (1984) found that hairy vetch can supply $90\text{–}100\,kg\,ha^{-1}$ of fertilizer N, and Utomo et al. (1990) reported as much as $200\,kg\,N\,ha^{-1}$ of fertilizer N equivalence from hairy vetch. In addition, during the rainy season, rhizodeposition of C during cover crop growth may have contributed to an increase in heterotrophic and denitrifier activity under the WLCC systems.

The first significant increase in N_2O emissions in the rainy season under both SDI and FI occurred in March when, 12 days prior to gas sampling, the cover crop had been mowed and incorporated. At this time, NO_3^- concentrations were relatively low but with significantly higher NO_3^- levels occurring under WLCC compared to NCC. Varco et al. (1987) found that 47% of a vetch cover crop had mineralized within 15 days of incorporation. Though large peaks in N_2O emissions occurred following the June fertilization event in FI, it appeared as though nitrification of organic N inputs were also contributing to N_2O emissions. The FI–WLCC treatment exhibited peaks in N_2O emissions nearly three times those from the FI–NCC treatment. The addition of high N inputs from the vetch/pea cover crop, might have also primed the soil, increasing the mineralization of soil organic N (Poudel et al., 2001).

The WLCC treatments had 3 years of winter legume cover crop input and it is likely that there was a significant buildup of both labile C and N in these systems compared to the NCC systems. Results from this study show that both total C and soil NO_3^- (Fig. 4) were highest in the WLCC systems. The cover crop in this study contributed significant levels of both C and N to the WLCC treatments, likely causing an excess of N and increased amounts of labile C in these systems and potentially enhancing heterotrophic activities. Azam et al. (2002) were able to demonstrate a positive correlation between the amounts of easily available C on N_2O emissions, with

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N_2O rates more than doubling in the presence of glucose. Similarly, Haung et al. (2004) found an intimate relationship between plant residue-derived N_2O and CO_2 emissions, with emissions increasing with increasing dissolved organic C. They were also able to show that N_2O emissions and dissolved organic C concentrations decreased as the C:N value of the residue input increased. Their study, along with reports from other authors such as Granli and Bockman (1994) and Hadas et al. (2003) support our conclusion that the addition of the C and N from the low C:N legume input under WLCC accounts for the observed significant increases in CO_2 and N_2O under the FI–WLCC treatment. During the growing season, the drier soils under SDI, compared to FI probably retarded cover crop biomass decomposition (Shelton et al., 2000). As a result, lower levels of dissolved organic carbon and mineralizable N may have been present in the SDI–WLCC soils, thus explaining the less dramatic impact of cover crops on CO_2 and N_2O production when combined with SDI. In this study, the fertilizer rate was not adjusted to account for the amount of cover crop-N added to the WLCC treatments in order to keep fertilization rates similar among treatments. However, in practice, even if fertilization management is adjusted for cover crop-N inputs, increases in labile C and DOC will nonetheless still present an opportunity for stimulating microbial activity and denitrification rates emissions.

The use of a non-N fixing cover crop such as oats or a cover crop like rye with a deeper root system and higher C:N ratio may lessen the impact of cover crops on N_2O emissions as deeper roots are better at pulling out residual soil-N (McCracken et al., 1994) and non-N fixing plants will provide less total N to the soil that may be potentially denitrified (Rosecrance et al., 2000; Baggs et al., 2000; Novoa and Tejeda, 2006).

5. Conclusion

An important implication of the present field study is that, in measuring CO_2 and N_2O event-based emissions in irrigated agriculture, it is essential to consider not only the growing season but also the periods between post-harvest and planting. Under the SDI–WLCC treatments, CO_2 and N_2O emissions were lower during the growing season compared to FI–WLCC treatments but were similar to FI during the rainy season, suggesting a delayed effect of growing season management. A second year of GHG emission data and greater sampling frequency during the winter would have proved beneficial to help corroborate results on the effect of irrigation management on winter emissions and perhaps validate the timing and occurrence of unusually high N_2O and CO_2 pulses.

The use of a winter legume cover crop had the greatest effect on GHG emissions compared to all other treatments. This was especially the case under FI during the growing season, where the interaction of FI–WLCC increased mean N_2O emissions by $60\,\mu g\,m^{-2}\,h^{-1}$ and mean CO_2 emissions by $135\,mg\,m^{-2}\,h^{-1}$ compared to FI–NCC. However, increases in N_2O and CO_2 related to the use of a winter legume cover crop were significantly reduced when combined with SDI. Thus, under cover-cropped agroecosystems, the conversion from FI to SDI may lead to potentially large reductions in GHG emissions that would otherwise be substantial under FI.

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