Use of Conservation Tillage, Subsurface Drip Irrigation and Cover Cropping to Reduce Soil Carbon and Nitrogen Emissions and Sequester Soil Carbon

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Summary

We compared the affect of subsurface drip irrigation (SDI) to furrow irrigation (FI) on GHG emissions in different tillage; standard (ST) and conventional (CT) and cover crop; no cover crop (NCC) and winter legume cover crop (WLCC) treatments. Our results show that in estimating greenhouse gas (GHG; CO_2 and N_2O) emissions in irrigated agriculture, it is essential to consider not only the growing season but also the periods between post harvest and planting. Under all SDI treatments, there was significantly less CO_2 and N_2O emissions compared to all FI treatments during the growing season, except in the ST-NCC treatment for CO_2 and in the CT-NCC treatment for N_2O emissions. The largest difference in GHG emissions were in the SDI-WLCC treatments compared to the FI-WLCC treatments, with as much as a 35% reduction in CO_2 emissions under the SDI-CT-WLCC and a 75% reduction in N_2O emissions under the SDI-ST-WLCC treatment, compared to FI in the growing season. However, during the rainy season, SDI CO_2 and N_2O emissions were higher compared to FI emissions, suggesting a lag effect of growing season management. The SDI-CT treatments exhibited 50% higher N_2O emissions compared to the FI-CT treatments during the rainy season. Annual cumulative CO_2 emissions were lower in SDI by 3.4- 5.4% compared to FI with the exception of ST-NCC. Annual N_2O emissions were lower in SDI only under the ST treatments but by as much as 68%. The cover crop treatments exhibited both higher total soil C and N and soil moisture. The WLCC treatments increased both CO_2 and N_2O annual emissions regardless of tillage or irrigation. However, the influence of a cover crop during the growing season was only evident in the FI systems. The potential for SDI to reduce GHG emissions is influenced by both tillage and cover crop when compared to FI. While significant reductions in N_2O emissions can be achieved under standard tillage by switching from FI to SDI, cover crops significantly increased both N_2O and CO_2 emissions regardless of irrigation management. By maximizing cover crop N recovery, system N losses via denitrification can be significantly reduced in SDI as well as in FI.

Objectives

The specific goals of this research were to determine differences in CO_2 and N_2O emissions, C budgets, and water use efficiency between various combinations of irrigation (subsurface drip (SDI) and furrow irrigation (FI)) and tillage (standard (ST) and conservation (CT)) with and without a cover crop (WLCC and NCC).

These management systems were analyzed for:

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1. Differences in CO_2 and N_2O emissions
2. Intra-treatment plot spatial variability in CO_2 and N_2O emissions
3. Diurnal and seasonal trends in CO_2 and N_2O emissions
4. Carbon sequestration
5. Water inputs and water use efficiency.

Approach and Procedures

Field Site

The experimental plots containing processing tomatoes was located at the University of California, Davis, Sustainable Agriculture Farming Systems (SAFS) facility. The experimental design consisted of the main treatments of SDI and FI, subplot treatments of CT and ST, and sub-subplot treatments of WLCC and NCC with three replications. The ST consisted of tillage operations typical of Yolo County tomato growers, and the CT operations consisted of one pass with a strip tiller to facilitate transplanting. The cover crop treatment was a mixture of Lana Vetch and Austrian Pea.

Irrigation and Fertilization

The subsurface drip irrigation events were approximately every two to three days and furrow irrigation events every five to 10 days. In the FI plots, 112 kg N/ha of fertilizer was side dressed at the start of the growing seasons, whereas in the SDI, fertilizer was applied in small increments through the drip tape (fertigation) to match crop uptake. A total of 112 kg N/ha was added via fertigation. All treatments received a N-P-K pre-plant side dressing of 50 kg N per ha.

Soil Sampling

Soil samples and tomato and cover crop plant tissue samples were taken throughout the year during tomato and cover crop growth. The soil samples were analyzed for total C and N, NH_4, and NO_3 and the tissue samples for total N and C content.

GHG Sampling

CO_2 point measurements were made using a portable infra-red gas analyzer (Licor 8100). N_2O emissions were measured from gas samples taken from vented chambers and immediately analyzed on a gas chromatograph. CO_2 and N_2O effluxes were measured throughout the growing season every 10 days, alternating between one or two days before or after furrow irrigation. During the rainy season (post harvest to tomato planting), gas measurements were taken every three weeks. Gas samples were taken from three sites within each treatment: in the plant line, shoulder of the bed, and furrow. Soil moisture and temperature were taken at the time of each gas sampling event.

Results

Crop Yields

Figure 1 shows harvest yield by treatment for 2005 and 2006 growing seasons. The FI treatments have slightly higher yields, but there is no statistical significance between irrigation treatments. The ST treatments outperformed the CT treatments across all systems in 2005 and 2006. Overall tomato yields for 2006 were much higher, compared to the 2005 season, and can be explained by planting date and climate differences between years. For example, there was unfavorable weather in May and early June of 2005.

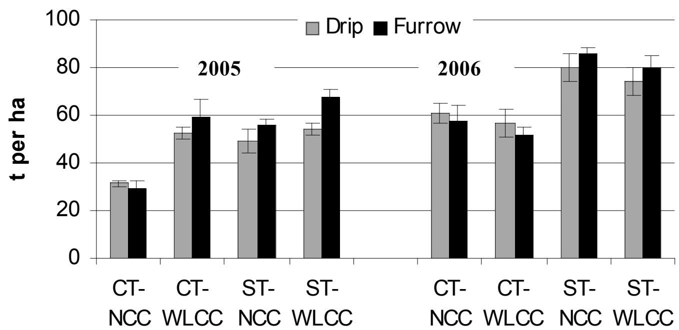


Figure 1. Machine harvest tomato yield in metric tons per ha for the 2005 and 2006 growing season.

Irrigation Inputs

Irrigation inputs during the 2005 and 2006 growing seasons were tracked using separate water gauges for SDI and FI (*fig. 2*). The amount of water applied per irrigation event in SDI was equal among all sub treatments (ST, CT, WLCC and NCC), whereas in the FI treatments, water inputs varied from plot to plot. Under FI, each plot could be treated separately and irrigation was stopped for individual plots once desired moisture was achieved. Water use efficiency (WUE) was calculated as crop yield per amount of total water applied in the growing season. For both the 2005 and 2006 season, SDI had a greater WUE compared to FI regardless of tillage or winter cover. The treatments with highest WUE were SDI-WLCC for both standard and conservation tillage in 2005 and SDI-CT in 2006. The lowest WUE was in the FI-CT-NCC treatments for both years. Averaging across the tillage and cover treatments, the SDI plots had between 40 and 50% higher WUEs compared to that of the FI plots.

	SDI	*FI*
2005	*32.65*	*60.01*
2006	*15.01*	*34.90*

Figure 2. Water inputs by irrigation for 2005 and 2006 (in/acre).

Soil samples collected throughout the study were analyzed for total soil organic C (SOC). The results for the two-year period between 2005 and 2007 for most treatments were slightly high for an average agricultural system (*fig.3*). Typical values for SOC increases under agriculture can be up to 0.5 tons, depending on cropping system management such as organic versus conventional or the user of winter cover crops (Poudel et al. 2002). There appeared to be little negative effect from irrigation or tillage on C storage except in the ST-NCC treatment. As was expected, the presence of a winter cover crop resulted in the greatest increase in soil C.

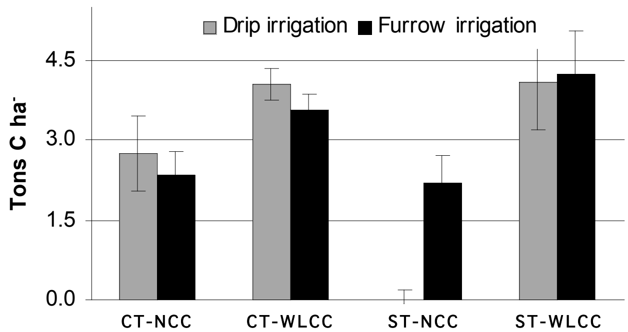


Figure 3. Amount of increase or decrease in soil organic carbon in the top 30 cm of the soil over a two-year period between 2005 and 2006. Error bars are standard error.

CO_2 and N_2O Soil Emissions

In this study, the differences in the soil wetting patterns between the two irrigation treatments (SDI and FI) were expected to produce distinct wetting patterns and soil moisture status. This will likely lead to differences in the spatial distribution CO_2 and N_2O soil emissions relative to irrigation management. In order to capture and compare the spatial variability across a treatment plot, field-point measurements for both CO_2 and N_2O were taken from three sites across each treatment plot, representing varying degrees of soil wetness under irrigation management. The spatial variability of gas emissions revealed from growing season measurements were related to soil moisture, a result of irrigation wetting patterns (*fig. 4*). During the growing season, the SDI treatments often had its highest gas emission rate in the plant line, just above the drip tape and soil wetting zone, whereas FI exhibited higher emission rates near the furrow in which the bed was typically above 60% soil water content. Furthermore, the difference in emission rates across the measurement sites were far more variable under SDI compared to FI, in which emission rates were more similar from plant line to furrow (*fig. 3*). In the rainy season, the spatial characteristics of GHG emissions in the two irrigation treatments were different from those exhibited during the growing season. Figure 3 shows the spatial distribution of CO_2 emissions in August and February of 2006, with a more equally distributed emission rate across the treatment bed for both SDI and FI in winter. This distribution for both seasons is typical for most of the sampling dates for both CO_2 and N_2O. However, measurements from several sampling dates during the rainy season showed considerably higher emissions in the furrow site under SDI compared to the other sampling sites as well as to the FI emissions.

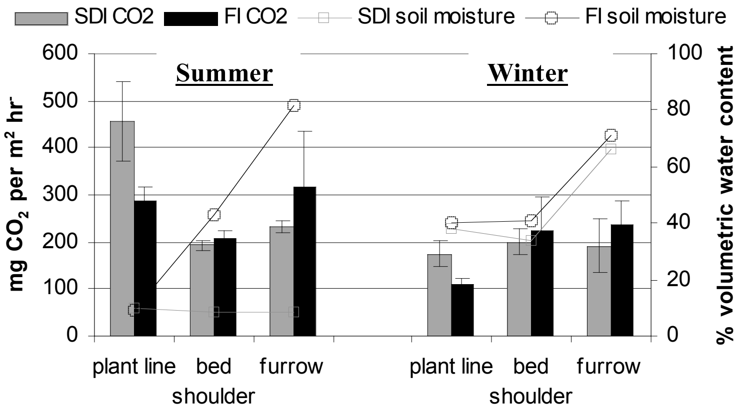
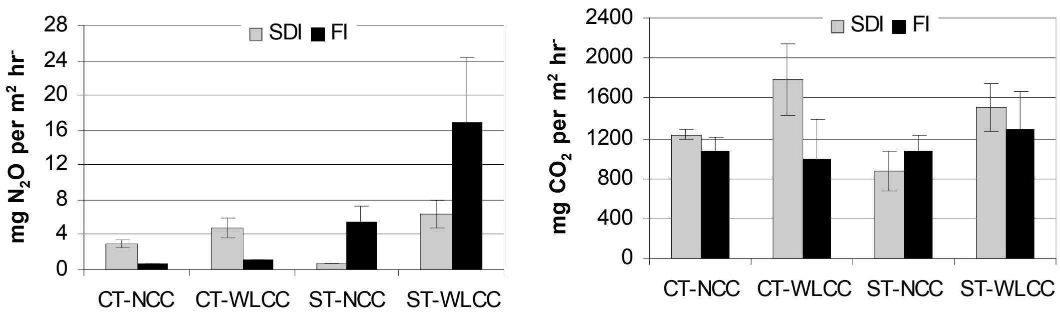


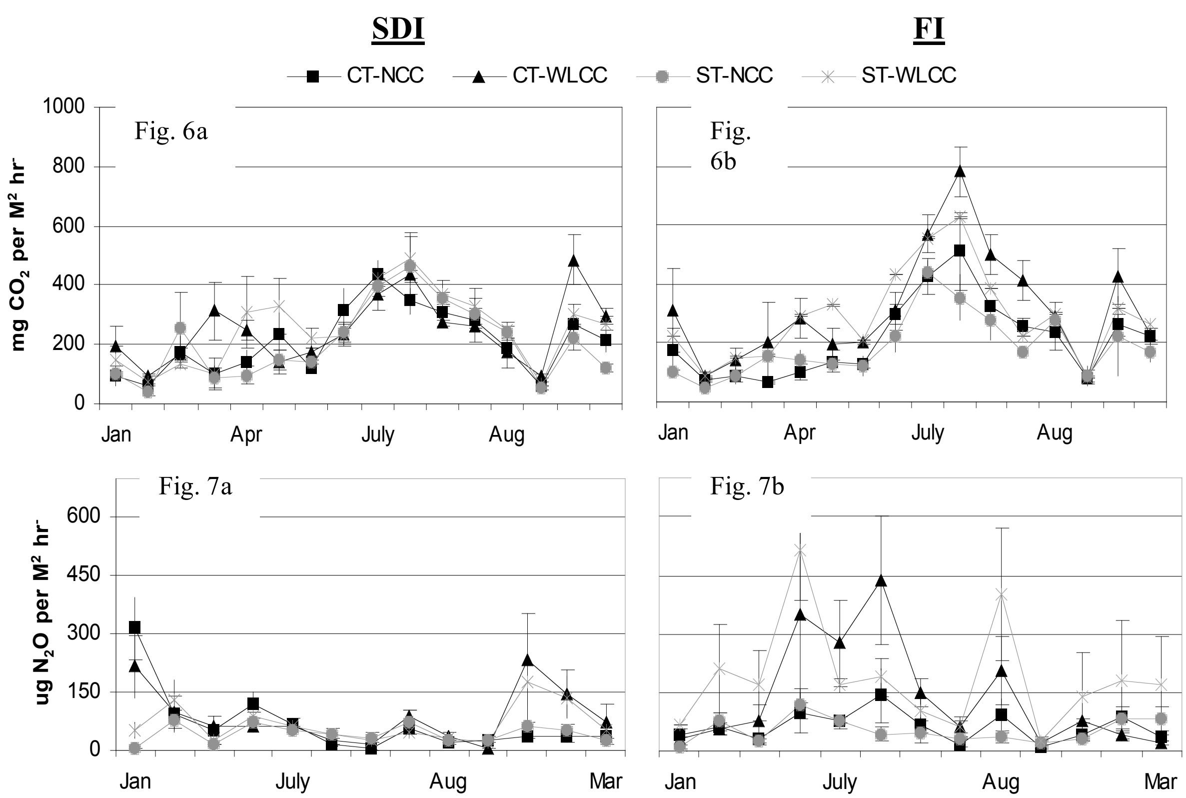
Figure 4. Spatial distribution of soil CO_2 production rates and soil moisture at 12 cm on August 4 and February 15, 2006. Measurements were taken from the plant line, shoulder of the bed and furrow for both SDI and FI treatments. Error bars are standard error.

In order to compare CO_2 and N_2O emission among treatments, GHG gas measurements from the three sampling sites within each treatment plot (plant, shoulder, and furrow) were grouped using a weighted average, based on soil wetting areas. Emissions for CO_2 ranged from < 200 mg CO_2 m^{-2} hr^{-1} to > 500 mg CO_2 m^{-2} hr^{-1}during the growing season (May 15 to August 31, 2006), although values greater than 400 mg CO_2 m^{-2} hr^{-1} were less common (*figs. 5a and 5b*) and were generally observed in the FI treatments following fertilization and tillage events. In the rainy season (October through May), CO_2 emissions were most often < 200 mg CO_2 m^{-2} hr^{-1}. Exceptionally high emissions were recorded on November 4th, 2006 (upwards of 1500 mg CO_2 m^{-2} hr^{-1}) two days following the first substantial rainfall (1.08 in) of the season. Furthermore, temperatures for this sampling date were relatively warm (65° F) and much of the freshly mulched tomato residue was still on the soil surface or had recently been tilled in, in the ST case. Similarly, N_2O emissions on this sampling date also exceeded normal emission rates (~ 5 mg N_2O m^{-2} hr^{-1}). To verify the high emissions, a second sub-sampling occurred on November 5 and although rates for both CO_2 and N_2O had already begun to drop, emissions were still high. Though these values are important to consider, they likely represent an anomaly related to the accumulation of labile C and inorganic N before winter rain onset. These high values from November 4 are shown separately from other point data in figures 5a and 5b.



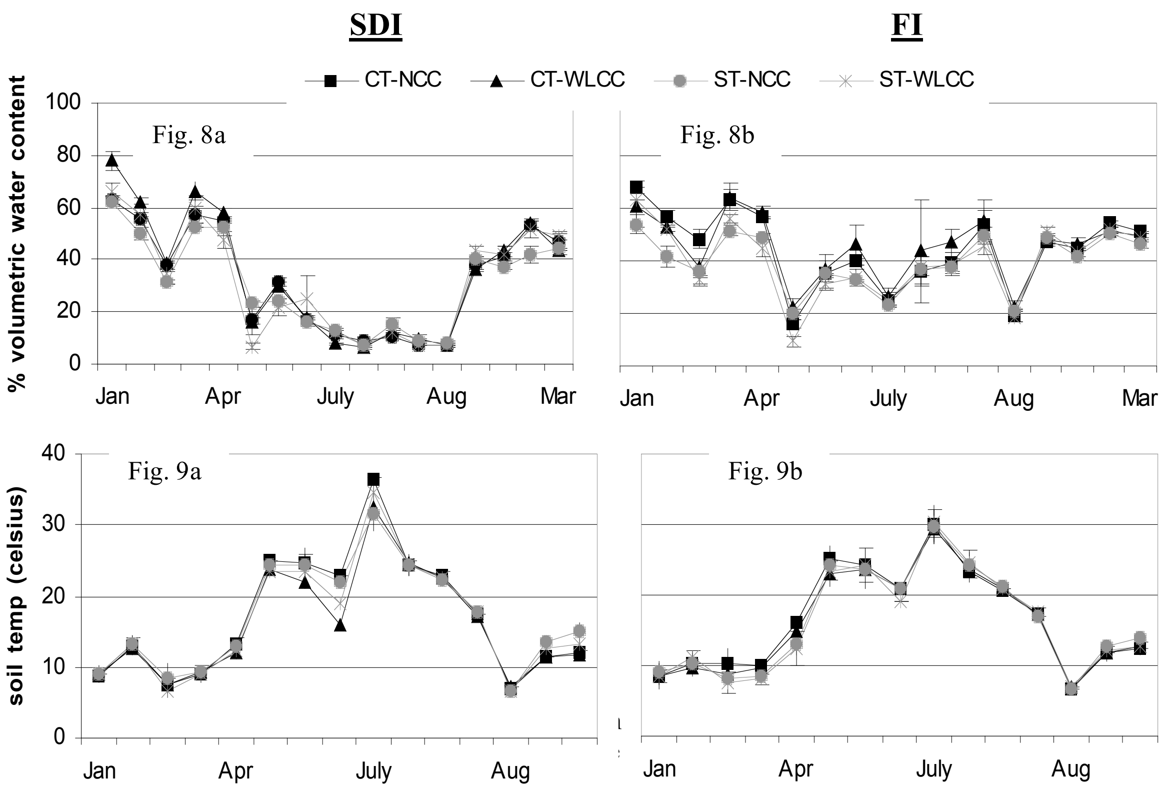
Figures 5a and 5b. N_2O and CO_2 emissions from November 4, 2006. Error bars are standard error.

On November 4, N_2O emissions from SDI were nearly double the rate of the FI emissions under the CT treatments but much lower than FI under the ST treatments. The FI-ST-WLCC treatment exhibited N_2O emissions more than twice those from any other treatment (17 mg N_2O m^{-2} hr^{-1}). CO_2 emissions from this sampling date were equal or higher under all SDI combinations compared to FI except in the ST-NCC treatment.



Figures 6 and 7. Point CO_2 and N_2O emissions from Jan 2006 to March 2007 for SDI (a) and FI (b). Error bars are standard error.

Differences between treatments in CO_2 and N_2O emission rates varied significantly by sampling date (*figs. 6 and 7*). Irrigation significantly affected temporal variability. Under the SDI treatments during the growing seasons, CO_2 in all systems (tillage and cover crop combinations) remained generally low compared to the FI treatments (*figs. 6a and 6b*). Furthermore, the change in emission rates from one sampling date to the next under SDI was relatively small and the variability between SDI treatments was also small, although SDI CO_2 emissions rose continuously throughout the season, peaking around July 6th. In comparing the FI systems, we see a much larger degree of change in emission rates between sampling dates during the growing season as well as higher variability between FI treatments. For N_2O emissions this phenomenon is more pronounced (*figs. 7a and 7b*), with relatively low and consistent N_2O emission rates between sampling dates under SDI compared to FI in the growing season. The variability of N_2O emissions within treatments under FI is especially high for the WLCC systems, which often had the highest rates of N_2O emissions. The trend of consistent emission rates under SDI and variable emissions under FI during the growing season is analogous to the trend in the amount of irrigation applied under SDI and FI (*fig. 10*). Under SDI, each irrigation event has a similar amount of water applied; keeping soil moisture levels steady, whereas, the amount of water applied under FI varies from one irrigation event to the next, resulting in a distinct wet-dry cycle.



Figures 8 and 9. Percent soil water content at 12 cm for SDI (8a) and FI (8b) and soil temperature at 6 cm for SDI (9a) and FI (9b). SO: CIMIS database, Davis station. Error bars are standard error.

Under SDI, water is applied in frequent but small amounts throughout the growing season, whereas under FI, water is applied much less often but in far greater quantities. The soil moisture values for SDI and FI, taken on each gas sampling date (*figs. 8a and 8b*) follow a similar pattern as the CO_2 and N_2O emissions over the course of the growing season, in which volumetric moisture content for SDI remains relatively steady around 15% and fluctuates from 20% to 60% under FI. The ST-WLCC treatment in FI also had the highest soil moisture levels for all but two of the sampling dates. On the other hand, the ST-NCC system under FI exhibited N_2O emission rates similar to those of the SDI systems.

The rainy season soil moisture values for FI were only slightly higher to those during the growing season; however, in the SDI systems soil moisture was much higher in the rainy season compared to the growing season and likewise so were N_2O emissions. Though all of the SDI systems had lower emission rates during the growing season compared to FI, measurements from the rainy season were often higher or equal to those under FI for both CO_2 and N_2O despite no difference in soil moisture between SDI and FI. The rainy season CO_2 emission rates for both SDI and FI were generally lower than those from the growing season; however, the SDI rainy season measurements were not only generally similar or greater to FI emission rates but also exhibited far more variability between treatments and sampling dates than what was seen during the growing season. The change from a relatively steady to a more erratic gas production rate in the rainy season under SDI may again be due in part to the supply of water, with more irregular water inputs via precipitation events and thus large changes in soil moisture (*figs. 10 and 8a*).

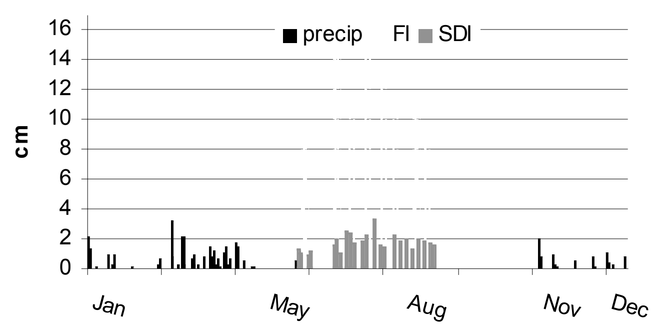


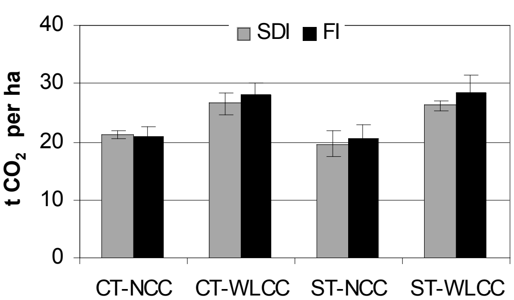
Figure 10. Daily precipitation (cm) (SO: CIMIS database; Davis Station) from January 1, 2006, to December 31, 2006 and FI and SDI irrigation events in cm of water applied per event.

From the growing season to the rainy season, large increases in N_2O emissions were seen in the SDI-CT treatments regardless of cover crop. During both the winter and spring, N_2O emissions were highest under the SDI-CT treatment (between 150 and 300 $\mu g\ N_2O\ m^2$-2 hr^{-1}) compared to all other treatments, except the FI-ST-WLCC treatment, which also had values near 150 and 200 $\mu g\ N_2O\ m^2$-2 hr^{-1}. The WLCC treatment also appeared to have an affect on CO_2 rainy season values with at least 60% of all sampling dates having the 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.

Soil temperature was recorded at the time of each gas sampling date (*figs. 9a and 9b*). With the exception of a few sampling dates, differences in soil temperature between treatments were negligible.

In order to estimate total annual CO_2 and N_2O emissions, field-point measurements were integrated overtime. Each point measurement was adjusted for daily temperature fluctuations using Q_{10} values calculated from diurnal measurements and air temperatures (Davidson et al. 2006 ; Lloyd and Taylor 1994).

Annual emissions of CO_2 were higher under the WLCC treatments compared to the NCC treatments regardless of tillage and irrigation management (*fig. 11a*). However, the effect of the main treatment irrigation was small. There did not appear to be any tillage effect on GHG emission within and among systems. For annual N_2O emissions, the difference under SDI and FI in ST and CT were pronounced (*fig. 11b*). The SDI-ST systems exhibited significantly less cumulative N_2O emissions compared to the FI-ST systems. However, the SDI-CT systems appeared to have higher cumulative N_2O emissions than the FI-CT systems. The effect of a cover crop was most significant in the FI-ST systems where a cover crop more than doubled cumulative N_2O emissions (*fig. 11b*). Taking only the integrated values for the growing season, N_2O emissions were higher by 60% in the CT-WLCC system under FI compared to SDI, however, including the rainy season emission rates in the annual total diminishes the irrigation-induced difference in CT-WLCC. Similarly, the CT-WLCC system under FI for the cumulative growing season CO_2 values shows emissions 35% higher compared to those under the SDI-CT-WLCC system. In fact, all of the SDI treatments had significantly lower cumulative CO_2 values for the growing season with the exception of the SDI-ST-NCC system. In figure 12, the effect of switching from a FI system to a SDI system on emission rates for CO_2 and N_2O are shown as a percent increase or decrease in annual emissions under SDI when compared to FI. Based on the integrated values shown in figures 11a and 11b, annual emissions of CO_2 were estimated to decrease under SDI in all of the systems except the CT-NCC.



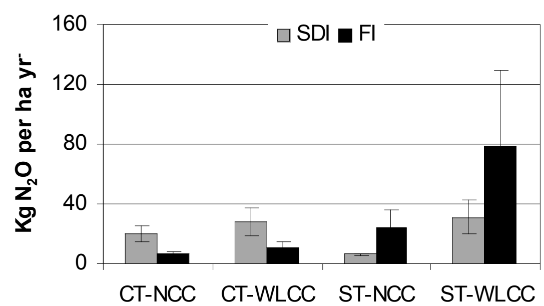


Figure 11a and 11b. Cumulative CO_2 (11a) and N_2O (11b) emissions from January 2006 to Janurary 2007. Total annual emissions were estimated through numerical integration after all point measurements were adjusted for diurnal changes using seasonal Q_{10} values. Error bars are standard error.

The ST-WLCC system had the largest reduction in CO_2 emissions under SDI (5.4%), however, none of the SDI-induced reductions were significant given high standard errors for all of the CO_2 values. Significant decreases in N_2O emissions were achieved using SDI for the ST treatments only. Alternatively, the CT treatments show large increases in annual N_2O emissions when SDI is applied compared to FI.

Treatment	CO_2	N_2O
CT-NCC	2% (± 8)	67% (± 3)
CT-WLCC	-4% (± 10)	59% (± 1.6)
ST-NCC	-3.4% (± 11.8)	-68% (± 12)
ST-WLCC	-5.4% (± 7.7)	-50% (± 16)

Figure 12. Percent difference between FI and SDI in cumulative annual CO_2 and N_2O emissions. A negative value indicates a reduction in emissions under SDI and a positive emission rate indicates an increase in cumulative annual emissions under SDI. Standard error (±).

Discussion

Much research has shown that the rate of N_2O emissions increase with increasing soil moisture (e.g., Dobbie et al. 1999; Abbasi and Adams 2000; Akiyama et al. 2004). However, most of these studies indicate significant N_2O production only after a water-filled pore space threshold has been reached, usually between 60 and 75% (Aulakh et al. 1991; Bateman and Baggs 2005; del Prado et al. 2006) resulting in a non-linear rate of N_2O production with increasing water-filled pore space. While most of the studies cited above were lab incubations, our field results do not appear to show a significant relationship with GHG production and soil moisture. All treatment CO_2 and N_2O rates correlated against soil moisture have an R^2 value below 0.3. It is noteworthy, however, that under incubations most controlling factors for CO_2 and N_2O production are kept constant, whereas in the field it is expected that factors such as soil moisture and temperature, soil physical properties, and C and N inputs all vary spatially and temporally. Thus, the relationship between CO_2 and N_2O production and soil moisture is further complicated by variables such as bulk density, total C and N availability and soil water holding capacity.

Irrigation Effects

Temperature and moisture have been shown to have the greatest effects on soil respiration (Rochette et al. 1991; Wang et al. 2000) while moisture and soil N are the two principle variables in controlling N_2O production (Firestone 1982). The production of both CO_2 and N_2O soil emissions often varies over both space and time, principally due to the heterogeneity of soil moisture, substrate availability, and at times the type and timing of tillage operations (Swift et al. 1979). Under FI, a large portion of the soil profile is wetted to near saturation during irrigation whereas under SDI the wetting area is smaller and more uniform and the irrigation events are more frequent with lower amounts of water applied per event. The efficient water and nutrient (fertigation) delivery of SDI was hypothesized to reduce CO_2 and N_2O emissions due to the lower amount of available C and N and limited microbial activity through spatial limitations of water. From this study, we have been able to show that the effect of SDI on greenhouse gas emissions is temporal and is further influenced by the sub treatments of tillage and cover crop.

Results for the 2006 growing season show that SDI had slightly lower CO_2 emissions across all tillage and cover treatments compared to FI, and that this difference was even more pronounced for N_2O emissions, especially under the WLCC treatments. However, when the rainy season is considered, the SDI treatments often had similar, if not greater, rates of N_2O and CO_2 production, except in the case of the ST treatments under FI. The furrow sites in the SDI plot beds, which during the growing season had relatively low emissions as well as very low soil moisture under SDI, were the sources of greatest CO_2 emissions under SDI in the rainy season. In other words, the previously driest sites during the growing season emitted the most CO_2 during the rainy season. The accumulation of labile organic matter and N likely explains the increased CO_2 emission during the winter in SDI. The SDI-CT treatment showed especially high N_2O production rates during this time, so much so, that the relatively low N_2O emissions under SDI-CT during the growing season were rendered irrelevant in terms of annual emission rates. This data suggests that the rainy season has more of an effect on the SDI systems in producing CO_2 and N_2O than it does in the FI systems. One explanation for higher CO_2 rainy season values under SDI could be that, the SDI systems had greater amounts of soluble C in the topsoil that had not been mineralized during the growing season due to moisture-limited soil conditions under SDI. The increase in dissolved organic C following the rewetting of dry soils has been shown in both field and laboratory studies (Ruser et al. 2006). Not only is there enhanced microbial activity and turnover following rewetting after dry periods, but C protected in soil aggregates may be released by the disruption of soil from water infiltration (Lundquist et al. 1999). Emissions of N_2O were considerably higher during the rainy season under SDI for the CT treatments only, compared to the FI-CT treatments, indicating an interaction between irrigation and tillage during the rainy season. It should be noted here that the SDI-CT treatment plots appeared to be the most compacted and were the most difficult plots in the field to penetrate with field equipment and sampling implements such as soil augers, thermometers, and TDRs. In a study conducted by Ruser et al. (2006) soil compaction from tractor traffic in a potato field led to higher N_2O emissions. They suggest the reason for higher N_2O emissions under compacted areas was largely a result of increased water-filled pore space from the reduction in pore size and continuity.

The unusually high emission rates recorded on November 4 for both CO_2 and N_2O likely influenced total annual emission rates. Under the SDI-CT treatments N_2O emissions for this sampling date were much higher than the FI-CT treatments, this was also true for total annual N_2O emissions. N_2O emissions under SDI from November 4 were as high as 6 mg N_2O m^{-2} hr^{-1}, whereas all other sampling dates had emissions less than 0.5 mg N_2O m^{-2} hr^{-1}. N_2O rates exceeding 2 mg m^{-2} hr^{-1} are rare and some of the highest recorded N_2O measurements in agriculture (Matson et al. 1998).

Due to the fact the emission rates on November 4 were orders of magnitude higher than all other sampling dates will result in the values from November 4 carrying greater weight when calculating annual emissions. As a result, those treatments that exhibited the highest emissions on this date were also often the treatments with the highest total annual emissions.

Tillage

Regardless of irrigation, the CO_2 emissions under CT were almost always higher, compared to those under ST, regardless of treatment. This was true for both field-point measurements as well as integrated CO_2 values by season and annually. Much of the literature points to conservation tillage as having a potential to reduce soil CO_2 emissions due to the increase occluded C within aggregates (Oades 1984; Paustian et al. 1997). However, few of these studies have occurred on irrigated lands in semi-arid climates, such as that in the Central Valley of California. Recently, there have been some studies suggesting either no tillage effect or higher CO_2 emissions under conservation or no till practices compared to conventional tillage (e.g., Ellert and Janzen 1999; Lee et al. 2006; Liu et al. 2007). In a five-year study in Northern California on tomato-cotton rotations, Veenstra et al. (2007) found that while conservation tillage occluded more C initially, the C was not stabilized and was turned over within a year resulting in no difference compared to standard tillage.

Reduced tillage conditions often result in higher soil water content due to surface covers from crop residues as well as from higher levels of organic matter (Rice and Smith 1982). During the growing season, the FI-CT treatments consistently had higher soil moisture values compared to the FI-ST treatments. Thus, the higher moisture values under FI may have contributed to the higher CO_2 values during the growing season. Root respiration is also a large contributor to CO_2 emissions in agricultural systems. The FI-CT plots were heavily infested with weeds throughout the growing season and into the rainy season, despite several herbicide applications and hand weeding. Weeds were continually extracted from areas near gas sampling points so as to not influence measurements: however, it is likely that the higher weed population in the CT plots increased the amount of CO_2 coming from root respiration compared to that of the ST plots which had relatively low weed populations.

There did not appear to be a tillage effect for N_2O emissions except when combined with irrigation, as discussed above. However, higher N_2O emissions are often associated with conservation tillage practices, usually due to higher moisture contents but also may be to a higher amount of soluble C (Liu et al. 2007)

Winter Cover Crop

Both the SDI and FI systems showed higher N_2O emissions when combined with WLCC annually. There was also a positive interaction between FI and WLCC during the growing season but not between SDI and WLCC. Although, 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 denitrified, it also adds additional C and N via plant biomass as well as biologically fixed N that leads to increased CO_2 and N_2O emissions. The WLCC treatments had three years of receiving a winter legume input to the soil, and it is likely that there was a substantial build up of both C and N in these systems compared to the NCC systems, increasing substrate availability to microorganism. Results from this study show that both total C and N were highest in the systems with a winter legume cover crop. The release of organic N from cover crops is even greater when they have been incorporated, which may help explain why the FI-ST-WLCC had the highest rates of N_2O emissions compared to all other treatments in this study. However, for CO_2 emissions the FI-CT-WLCC treatment exhibited the highest emissions (followed by the FI-ST-WLCC treatment) perhaps because the CO_2 production was limited more by moisture and less by substrate availability. Furthermore, with increasing organic matter the water holding capacity in the soil also tends to increase (Shelton et al. 2000.). This could extend the time that the optimal conditions for N_2O and CO_2 production are present under the WLCC treatments, thus prolonging high levels of gas emission rates. The use of a non N-fixing cover crop such as oats may lessen the impact of cover crops on N_2O emissions (Rosecrance et al. 2000; Baggs et al. 2000; Novoa and Tejeda 2006).

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