

Carbon Dioxide Emissions and Spatial Variability Affected by Drip Irrigation Methods in a Pomegranate Orchard

Suduan Gao, Aileen Hendratna, Zejiang Cai, Tom Pflaum, Ruijun Qin, and Claude Phene

Abstract—Mitigation of greenhouse gas emissions is essential to combat climate change, and also for sustainable agriculture. Agriculture is facing a growing number of challenges including water shortage and environmental degradation that threaten crop production. In this research, field monitoring was carried out to evaluate the effects of drip irrigation methods and nitrogen (N) fertilization level on carbon dioxide (CO₂) emissions in a 5-year old pomegranate orchard. Surface drip irrigation (DI) and subsurface drip irrigation (SDI) were tested as main treatments. Three N application rates (50%, 100%, and 150% in reference to current practices) were applied as sub-treatments. CO₂ emission data were collected during the growing season. The CO₂ flux near the irrigation line was significantly higher from DI (ave. 2.67 $\mu\text{mol m}^{-2} \text{s}^{-1}$) than SDI (ave. 1.74 $\mu\text{mol m}^{-2} \text{s}^{-1}$). There were significant spatial variations surrounding a tree from DI but much less from SDI. However, no significant differences in cumulative CO₂ emissions were determined between DI (7.5–9.5 Mg ha⁻¹) and SDI (7.7–9.0 Mg ha⁻¹) due to small wetting areas under DI. These values may subject to error due to the limited number of sampling times in spatial variations. The higher DOC and water content in surface soil from DI contributed to the higher CO₂ emissions in comparison to SDI. The spatial variation should be considered to accurately estimate CO₂ emissions in orchard settings especially with irrigation systems. The SDI provides overall benefits of water savings, improvement on nutrient use efficiency, and reduction in total greenhouse gas emissions.

Index Terms—Greenhouse gas emission, high-frequency drip irrigation, surface drip irrigation, subsurface drip irrigation, fertigation.

I. INTRODUCTION

Carbon dioxide (CO₂) accounts for 82% of the total greenhouse gas (GHG) emissions in the USA [1]. As the

second largest terrestrial carbon (C) flux, soils around the globe have increased CO₂ emissions over the past few decades and are predicted to release more CO₂ with the climate change by increasing microbial consumption of plant debris and organic matter [2]. Soil, however, can help combat and adapt to climate change because of its ability to store large amount of organic C (carbon sequestration) when managed with sustainable practices [3].

Agricultural activities can have a great impact on CO₂ emissions because soils can serve as either a source or a sink [4], [5]. Conservation practices play important role in sequestering soil organic C such as manure amendment, residue incorporation, mulch, and increased cropping intensity that increase C input, and those practices slowing down decomposition of soil organic matter using no or reduced tillage [6]–[8]. Effective water and nutrient management also result in reduced CO₂ emissions [9]–[11], but these studies are inconclusive regarding irrigation method or the amount of water or source of fertilizer [12]–[14]. Irrigation and fertilization were found to increase CO₂ emissions [15]. Deficit irrigation was found with lower emissions [9], [10]. Subsurface watering was found to delay or have lower CO₂ emission flux [16]. However, some research showed no significant soil moisture effects [17]. In saline/alkaline soils, inorganic CO₂ diffusion and dissolution can contribute to reduced CO₂ flux [18]. More field data are needed that evaluate multiple environmental factors and determine irrigation and nutrient management practices on CO₂ emissions.

Soil respiration releases CO₂ from microbial and plant activities [7]. Microbial respiration can account for up to 99% of soil CO₂ emissions and root respiration can account for up to 50% [19]. Microbes decompose soil organic matter for their energy source and releases CO₂ and nutrients. This process can be affected by many environmental factors (soil temperature and water content) [20] and practices influencing these factors such as tillage or irrigation that affect soil air porosity [21]. Water content is one of the most important factors affecting soil respiration, and different irrigation system would impact water distribution in soil. Drip irrigation, especially subsurface drip, can increase water use efficiency with other benefits [22], but its effect on CO₂ emissions from irrigated field is not clear because of limited number of studies.

California (CA) is the most agricultural producing state in the United States with a total of \$50.13 billion (USD) output in 2017 [23]. San Joaquin Valley (SJV) (south part of the Central Valley of CA) is one of the most productive regions

Manuscript received February 12, 2020; revised March 19, 2020. This work was supported by the U.S. Department of Agriculture, Agricultural Research Service Base Funds. Mention of trade names or commercial products in this publication is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the U.S. Department of Agriculture. USDA is an equal opportunity provider and employer.

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in the world with an annual agricultural output exceeding \$30 billion (USD). The SJV's climate is Mediterranean, i.e., with hot/dry summers and cool/moist winters and all crops rely on irrigation. However, water shortage has become more frequent forcing the region to seek more efficient irrigation technology and drought tolerant crops, such as pomegranate (*Punica granatum L.*).

To evaluate water and nitrogen (N) requirement as well as their use efficiency affected by irrigation method and N application level, a field experiment was conducted from 2010–2015 in a pomegranate (var. *Wonderful*) orchard in the SJV. The field treatments included two irrigation methods as the main treatments: commonly used surface drip irrigation (DI) in the region and subsurface drip irrigation (SDI) and three N application rates as sub-treatments. Ayars *et al.* [22] reported the findings on treatment effects on yield, crop N requirement, and weeds. Tirado-Corbalán *et al.* [24] examined C and N dynamics from this field research. We also measured greenhouse gas nitrous oxide (N_2O) emissions for two years and the results were reported in Gao *et al.* [25]. The previous studies have concluded that SDI led to water savings and much lower weed pressure in comparison with DI and there was significantly higher N uptake in fruits from SDI at least in two out of the last three years of measurements [22]. Although soil N concentration was higher in subsurface soil under SDI from fertigation, using high irrigation frequency can reduce leaching potential [24]. The SDI resulted in significantly lower N_2O emissions than DI [25]. The objective of this paper was to evaluate the effects of drip irrigation method and N fertilization level on CO_2 emissions during growing season and evaluate spatial variations. The data were collected when the pomegranate orchard entered its fifth year.

II. MATERIALS AND METHODS

A. Study Site, Treatments, and Field Operation

Carbon dioxide emissions were measured in 2014 in the 1.4 ha pomegranate orchard established in 2010 at the University of California, Kearney Agricultural Research and Extension Center, Parlier, CA, which is situated within the SJV, USA. The soil was Hanford sandy loam (coarse-loamy, mixed, superactive, nonacid, thermic Typic Xerorthents). The soil has 17% water content at 33 kPa that can translate to a field capacity of ~ 26% (v/v) with an average bulk density of 1.55 g cm^{-3} [26]. Details on the project, soil property, and orchard operation can be found in Ayars *et al.* [22] and in Gao *et al.* [25]. All trees received the same amount of N fertilizers during the first two years to ensure uniform growth prior to different irrigation and fertilization treatments starting in 2012. The field used a split-plot design with two irrigation methods: DI and SDI as the main treatments, and three N application rates of 50, 100, and 150% of current practice as sub-treatments. Each treatment plot consisted of three tree rows with a total of seven trees in a row. Row spacing and tree spacing in a row was 4.9 and 3.6 m, respectively. Carbon dioxide emissions were measured during growing/irrigation season of 2014 in three replications. The middle row in each treatment plot was used for

monitoring. Both DI and SDI included two irrigation drip laterals with one on each side at a distance 1.1 m from the tree on soil surface for DI or buried at soil depth of 50–55 cm for SDI. Irrigation was triggered after 1 mm of crop water use measured in a lysimeter located within the field, thus the system can reach irrigation frequency as high as 8–12 times per day during summer.

For the different levels of N fertilization treatments, N-pHURIC® 10/55 (urea and sulfuric acid with 10% N and 18% S) was injected through irrigation system to all N1, N2, and N3 treatments first, additional N requirement for N2 and N3 was injected with ammonium nitrate (20% N or AN20), and all treatments received the same amount of P and K supply (Table I). Fertilizer application began in early May through September. Total N applied during the growing season was 54, 216 and 336 kg ha^{-1} for N1, N2, and N3 treatments, respectively.

TABLE I: FERTILIZATION RATES (kg ha^{-1}) FOR THREE LEVELS OF N TREATMENTS DURING 2014 GROWING SEASON IN POMEGRANATE ORCHARD

Fertilizers	Treatments		
	N1	N2	N3
Nitrogen (N-pHURIC)	54.3	54.3	54.3
Nitrogen (AN-20)	0	161.4	281.3
Total N	54.3	215.7	335.6
Phosphorous (H_3PO_4)	88.8	88.8	88.8
Potassium ($K_2S_2O_3$)	83.9	83.9	83.9

B. Soil Temperature/Moisture Monitoring, DOC Measurement

To demonstrate differences between the two irrigation systems, soil temperature and moisture was monitored for a week in May 2014. Soil temperature was measured using a HOBO® U12 Outdoor Datalogger (Onset Computer Corp., Bourne, MA, USA) with TMC20-HD air/water/soil temperature sensor. Soil moisture was monitored using a Decagon EM50 datalogger with Decagon Devices 10HS moisture sensor (METER Group, Inc., Pullman, WA, USA). Soil samples were collected at the end of growing season for dissolved organic carbon (DOC) analysis, which is better to correlate to soil respiration than other parameters. The analysis was done using a Teledyne Tekmar TOC Fusion Analyzer (Teledyne Tekmar, Mason, OH, USA) from soil extract. Soil was air-dried and sieved through 2 mm. The extract was obtained after mixing 50 g soil with 50 mL deionized water, allowed to stand undisturbed for 24 h, then shaken for 1 h on a reciprocating shaker, vacuum filtered through Whatman® no. 42 filter paper, diameter 90 mm, and then followed with another vacuum filtration through Millipore™ 0.45 μm nitrocellulose membrane, diameter 47 mm.

C. CO_2 Emission Measurements

A LI-8100A automated CO_2 flux system (model 8100-103, LI-COR® Biosciences, Lincoln, NE, USA) was used with a single 20 cm survey chamber to measure the emissions (Fig. 1). The system is automated, and designed to measure soil CO_2 efflux at soil surface. Similar systems had been used by

other researchers [27]–[29]. The system can be carried easily throughout the field. Details about the system can be found at https://www.licor.com/env/pdf/soil_flux/8100A_brochure.pdf. A collar that is designed specifically for the chamber was inserted into the surface soil prior to measurement with 3 cm as chamber offset (distance between soil surface and top of the collar). The system was programmed to make each measurement within 90 seconds upon chamber closure. Data could be processed for flux based on a linear or an exponential function. We chose the flux computed with the exponential function. The system also included a probe that is used to measure soil temperature and water content at 10–15 cm soil depth. Emission measurements were made twice per week from mid-May to mid-October. Data collection was made between 9:00–11:00 in the morning, which roughly represented average flux of the day based on diurnal flux changes monitored (see below). Continuous measurements were made in irrigation lateral areas where soil water content was the highest throughout the irrigation/growing seasons. Irrigation tubing from DI was removed during measurement and returned afterwards.

D. Spatial and Diurnal CO₂ Emission Measurements

Spatial and diurnal variation in CO₂ emissions surrounding trees during 24 hours was monitored twice during the growing season. The measurement was done every hour except from midnight to dawn (assuming little changes occurring during this time). The first measurements (7–8 May 2014) were made on the irrigation line for all six treatments in one replicate. The second measurements (4–5 June 2014) were made on two trees: one from DI and another from SDI at seven locations surrounding each tree (Fig. 2): between the tree and irrigation line (A), irrigation line (B), from the irrigation line towards center of alleyway at half way (C), center of alleyway between two tree rows (D), $\frac{1}{4}$ distance from the tree in a tree row (E), midpoint between two trees within a tree row (F), and midpoint between two trees, but in irrigation line (G).



Fig. 1. LI-8100A automated soil CO₂ flux system used in this study.

E. Data Processing and Statistical Analysis

Cumulative CO₂ emissions were estimated based on the flux measured during the growing season near drip lines and the spatial and diurnal variation determined surrounding trees from DI and SDI described above. Measured flux between 9:00–11:00 ranging from 87%–104% of average daily rates from 24-hour monitoring. Thus, the measured flux was assumed to represent daily average and used to compute

cumulative emissions by integrating with time for area affected by the irrigation. Emissions from other areas surrounding the trees were estimated based on the monitored spatial distribution results. Areas surrounding a tree were divided to different sections to estimate the total emissions from the whole field. Specifically, because large spatial variability was observed for DI, i.e., the highest CO₂ flux from irrigation line, lowest from alleyway, and small changes in tree rows, four sections were used to compute cumulative flux: tree line, irrigation line, halfway between irrigation line and midpoint of alleyway, and remainder of the alleyway. For SDI with small variability, two sections were used from tree row toward halfway to the center of alleyway, and the remainder of alleyway. These justifications were made based on the 24-hour flux measurements and believed to give a more reliable estimate for cumulative CO₂ emission loss in the orchard.

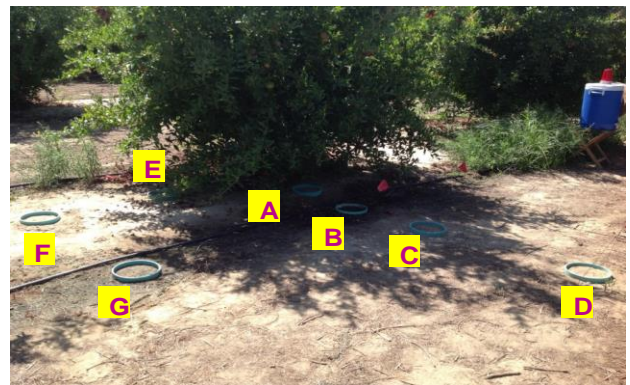


Fig. 2. Monitoring positions around a tree for measuring spatial variation of CO₂ flux.

Data on CO₂ emission rates, cumulative emissions, and soil DOC were statistically analyzed using SAS[®] software 9.4 [30]. For emissions, a split plot mixed model was used with irrigation, N level, and the interaction as fixed effects. The random effects are block and irrigation \times block. For the emission rate the focus was on the significant irrigation main effect. For cumulative loss, neither irrigation and N levels main effects were tested significant and an attempt was made on the N level main effect. For DOC in soil profile, a split plot, repeated measures, mixed model was used. The fixed effects are irrigation, N_level, depth and its interactions with others. The random effects are block, irrigation \times block, and irrigation \times N_level \times block. The latter 3-way interaction defines the experimental units for incorporating a first order, autoregressive covariance structure among the repeated measures in depth. Focus is on the significant irrigation \times depth interaction for which means and 95% confidence intervals were determined.

III. RESULTS AND DISCUSSION

A. Soil Moisture and Temperature

Soil temperature and moisture data monitored for a week in May 2014 are shown in Fig. 3. The DI showed much higher moisture than SDI in surface soils. Gao *et al.* (2019) [25] reported that soil water content increased as soil depth increased in SDI, but was relatively uniform under DI

because the high frequency irrigation resulted in surface soil (5 cm depth) near field capacity most of the time. Under SDI, much drier surface soil was monitored with higher water content at deeper depth. The data suggest that drip tubing buried near 50 cm has limited water movement upward. For DI, the higher surface soil moisture led to higher microbial activity and biomass including weeds [22] that are believed to contribute to the higher CO₂ emissions. As for soil temperature, small differences were observed between the irrigation methods (data not shown). The DI showed slightly lower temperature with an ave. 18.49 (± 3.25) °C and 19.06 (± 1.53) °C compared to 20.79 (± 3.29) °C and 20.86 (± 1.49) °C at soil depth of 5 cm and 15 cm, respectively, while air temperature remained the same (ave. 19.03 (± 6.67)).

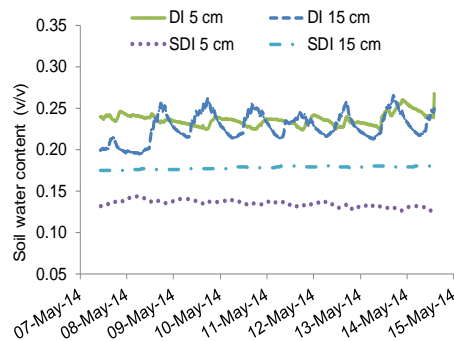


Fig. 3. Continuous soil moisture monitoring under DI and SDI during one week in May 2014. Treatments: DI=surface drip irrigation, SDI=subsurface irrigation. Numerical values are soil depth.

B. CO₂ Emission Rates

Results of the CO₂ emission flux during 2014 growing season in the pomegranate orchard are shown in Fig. 4. Consistently higher emission rates near the irrigation line were measured from DI than SDI throughout the growing season at all three N levels. The average flux values were 2.74, 2.44, and 2.82 $\mu\text{mol m}^{-2} \text{s}^{-1}$ from DI and 1.91, 1.62, and 1.69 $\mu\text{mol m}^{-2} \text{s}^{-1}$ from SDI, for N1, N2, and N3 treatments, respectively. Statistical analyses showed only irrigation effects was significant, and there were no significant effects of N level and interaction between irrigation and N level (Table 2). Estimated average emission rates for DI (2.67 $\mu\text{mol CO}_2 \text{ m}^{-2} \text{s}^{-1}$) were significantly higher than that from SDI (1.74 $\mu\text{mol CO}_2 \text{ m}^{-2} \text{s}^{-1}$).

C. Spatial Variability of CO₂ Emissions

TABLE II: ANOVA MIXED PROCEDURE TESTS OF THE FIXED EFFECTS ON CO₂ EMISSION RATES AND CUMULATIVE EMISSION LOSSES DURING 2014 POMEGRANATE GROWING SEASON

Type 3 tests of fixed effects				
Effect	Num of DF	Den DF	F Value	Pr>F
CO ₂ emission rates				
Irrigation †	1	10	44.64	<0.0001
N level ‡	2	10	1.35	0.3035
Irrigation × N level	2	10	0.48	0.6302
CO ₂ cumulative loss				
Irrigation†	1	12	0.01	0.9072
N level ‡	1	12	1.65	0.2326
Irrigation × N level	1	12	0.34	0.7196

† Irrigation treatment: DI, surface drip irrigation; SDI, subsurface irrigation.

‡ N level treatment: 50%, 100%, and 150% in reference to common practices.

Spatial variability surrounding a tree in the pomegranate orchard was much larger from DI than SDI (Fig. 5), Under DI, the highest emissions were observed near irrigation line and the lowest was from the center of alleyways while much smaller differences were observed under SDI. The data suggest that both water content and temperature affected CO₂ emissions. The diurnal temperature change is shown in Fig. 6. The CO₂ emission rate increase correspond to the soil temperature increase (Fig. 6), which explains the diurnal changes. The much higher emission rates from DI than SDI is due to difference in surface soil moisture from irrigation. Peak emission rates under DI is twice those under SDI

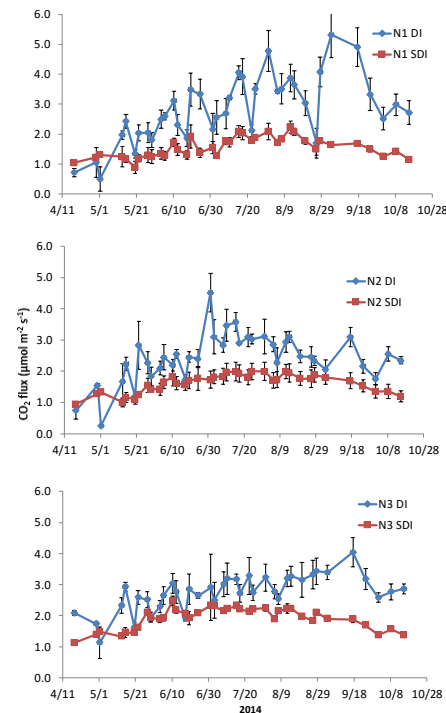


Fig. 4. Carbon dioxide emission flux measured in irrigation line affected area from a pomegranate field during 2014 growing season. Treatments: DI=surface drip irrigation, SDI=subsurface irrigation, N1, N2, and N3 = 50%, 100% and 150% in reference to common practices. Error bars are standard deviations of the mean ($n = 3$).

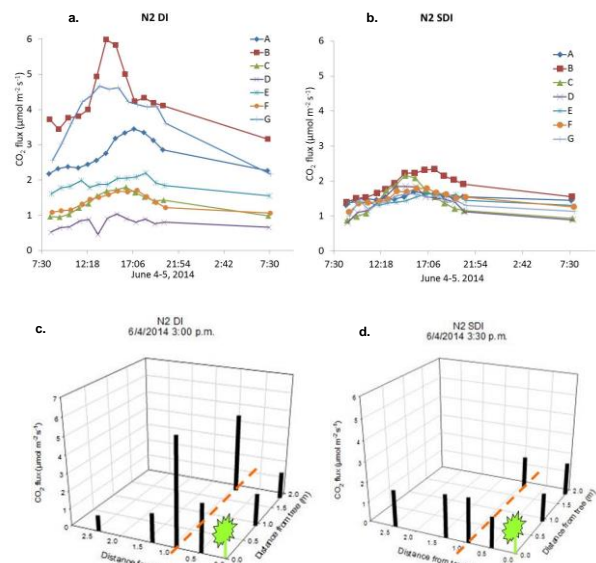


Fig. 5. Carbon dioxide flux measured at various location surrounding a tree from N2 level under DI or SDI. DI and SDI refer to surface drip and subsurface drip irrigation respectively; N2 refers to N application at 100% level in reference to common practices.

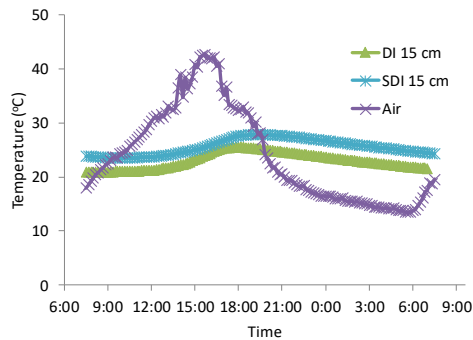


Fig. 6. Soil temperature measured on 4 June 2014 when spatial variability of CO₂ emissions was measured.

D. Cumulative CO₂ Emissions

Cumulative CO₂ emissions from the pomegranate orchard during the growing season are shown in Fig. 7. Statistical analysis showed that there were no significant irrigation nor N treatment effects. This was because although CO₂ emission flux can be much higher under DI than SDI near irrigation line, but the wetted area in the orchard accounts for no more than 25% of the total area. However, measurements for the spatial variability of CO₂ emissions were conducted only once, i.e., some errors may be encountered when using the data to justify emission flux for other times. For example, there appears no satisfactory explanation when the center of the alleyway under DI gave much lower CO₂ emissions than that under SDI (Fig. 5 c, d). Thus, more evaluations on spatial variability in CO₂ emissions are necessary under similar setting that would improve methodology to estimate total emissions from an orchard, especially under DI.

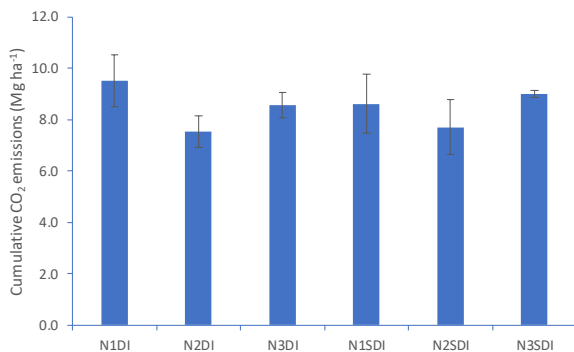


Fig. 7. Cumulative CO₂ emission estimates during irrigation season (April–October 2014) in a pomegranate field. DI and SDI refer to surface drip and subsurface drip irrigation respectively; N1, N2, and N3 refer to N application at 50%, 100%, and 150% in reference to common practices. Error bars are standard error of the mean (n = 3).

Average cumulative CO₂ emissions in our study are 8.54 and 8.44 Mg ha⁻¹ for DI and SDI, respectively. The cumulative emissions in the field from DI appear to be lower than values reported for other types of fields. Guo *et al.*, [20] measured 19.6 Mg ha⁻¹ CO₂ emissions from surface drip irrigated during a summer maize growing season in the North China Plain [20]. The lower CO₂ emissions in our study were possibly attributing to tree shading, and large dry surface areas in the field. Guo *et al.* [20] also found that cumulative CO₂ emissions on the irrigation pipes was larger than that between irrigation pipes. Edwards *et al.* [31] measured emissions from surface and subsurface drip (drip tape buried to 15 cm soil depth) irrigated tomato field for two years with

significantly higher cumulative emissions from surface drip than subsurface drip, but they attributed the difference to sampling time temperature difference and concluded that the irrigation methods did not have a direct impact on CO₂ emissions. Fares *et al.* [32] measured CO₂ emissions from different irrigation levels [75% (deficit), 100%, and 125% (excess) of reference crop evapotranspiration] using surface drip irrigation system and found no statistical differences among the irrigation levels. Our study had a much deeper subsurface drip irrigation (~50 cm depth) that showed restricted water movement to surface (Fig. 3) resulting in significantly lower CO₂ emissions near drip lines.

E. Relationship between CO₂ Flux and Soil Temperature and Water Content

A much stronger temperature correlation to CO₂ flux was shown under DI than SDI, but there is no clear correlation to soil moisture under either DI or SDI (Fig. 8). This might be because high irrigation frequency maintained the soil condition to be either wet (DI) or dry (SDI) most times temperature effect became dominant (Fig. 8a). The temperature effect was stronger under DI (Deeper slope) than SDI (Fig. 8b).

The observed CO₂ flux increase as soil water content increased from DI drip lines was due to enhanced microbial activities. This can be illustrated by the lower CO₂ emissions from drier surface soil under SDI compared to those from DI in our study. In a column study, Wei *et al.* [17] reported subsurface watering resulted in reduced CO₂ emissions. Sainju *et al.* [15] found that irrigation increased CO₂ emissions flux by 13% in compared with non-irrigation in North Dakota, USA. In comparison with different amounts of water irrigation to surface soil, Zornoza *et al.* [9], [10] showed deficit irrigation, especially with more than one dry period, significantly reduced CO₂ emissions in woody orchards in Spain. They found that although microbial biomass did not appear to be affected by deficit irrigation, β-glucosidase activity was significantly higher under full irrigation and positively correlate with CO₂ emissions, suggesting a significant fraction of CO₂ emitted from soil derives from degradation of organic matter.

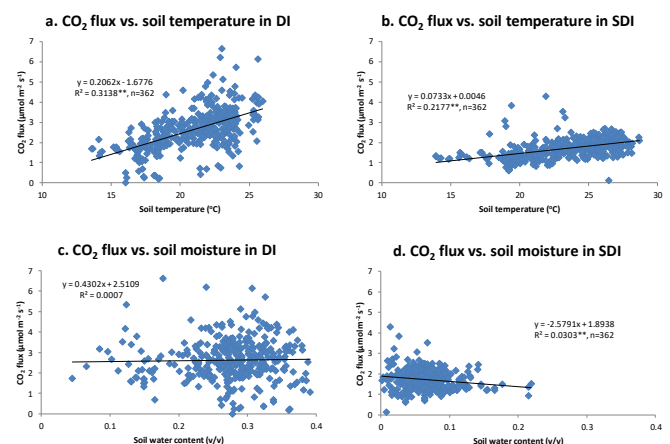


Fig. 8. Correlations between CO₂ emission flux and soil temperature or water content during growing season in pomegranate orchard.

F. Soil Dissolved Organic Carbon

Dissolved organic carbon is defined operationally as the

organic carbon with small sizes that can pass through a given filter size (0.45 micrometers is often used). The DOC includes the breakdown products from dead organic materials that serve as a food or energy source for the growth of microorganisms. Thus, higher DOC represents higher microbial activities or respiration. Statistical analysis showed that DOC in soil by end of pomegranate growing season were significantly affected by depth and interaction with irrigation (Table 3). While there were no significant differences in DOC at most soil depths between the irrigation treatments, DI did show a much higher DOC level than that from SDI in surface 15 cm soil (Fig. 9). Total soil organic C decreased as depth increased in both DI and SDI, but at 45 cm depth or below, SDI began to have slightly higher DOC. This trend agrees with soil total organic carbon (TOC) data that subsurface soil under SDI had similar or higher TOC than DI [24]. The data indicate higher microbial activities in surface soil under DI due to more available energy source, which could be from more dead leaves or weeds than SDI [22]. Although CO₂ production in subsurface soil could be high from SDI due to higher water content, it would be subject to a longer pathway before reaching the surface and emit to the atmosphere when chemical dissolution [18] could have occurred resulting in the much lower net emissions under SDI.

Nitrogen application levels did not affect CO₂ emission in this study. Both Ayars *et al.* [22] and Tirado-Corbal á *et al.* [24] have demonstrated that N3 treatment provided unnecessarily high N for the pomegranate demand although it resulted in highest TOC in soil. The no significant difference in DOC (Table 3) from the various N level may suggest that microbial activities were not limited by nutrients and possibly energy source, but more by moisture condition affected by irrigation methods. However, N₂O emissions were much higher at higher N application levels (25).

TABLE III: ANOVA MIXED PROCEDURE TESTS OF THE FIXED EFFECTS ON SOIL DOC DATA ANALYSIS BY THE END OF 2014 POMEGRANATE GROWING SEASON

Type 3 tests of fixed effects				
Effect	Num of DF	Den DF	F Value	Pr>F
Irrigation†	1	12.1	0.10	<0.7568
N level‡	2	12.1	0.28	0.7637
Irrigation×N level	2	12.1	1.27	0.3151
Depth§	3	27.8	41.84	<0.0001
Irrigation×depth	3	27.8	3.49	0.0289
N level × depth	6	29	0.65	0.6918
Irrig ×N level× depth	6	29	0.28	0.9423

† Irrigation treatment: DI, surface drip irrigation; SDI, subsurface irrigation.
‡ N level treatment: 50%, 100%, and 150% in reference to common practices.
§ Soil depth: 0-15, 15-30, 30-45, 45-60 cm.

G. Benefits of Subsurface Drip Irrigation

While CO₂ emission flux generally increased as soil water content increased, the relationship between water content and soil respiration components is not clear. Moinet *et al.* [33] studied soil respiration in relation to water content and soil organic C in a grassland ecosystem using ¹³C technique to partition total soil respiration (R_S) into its components soil heterotrophic respiration (R_H) and soil autotrophic respiration (R_A). They found that the R_H is insensitive to

change in soil water content, but is sensitive to organic matter accessible to microbes. R_S and R_A were strongly correlated and both showed strong linear relationship with gravimetric water content (W_S) and soil temperature (T_S) as well as DOC. R_H, however, was not related to variation in W_S and T_S, but was correlated with the amount of soil particulate organic matter, a labile fraction of C. They concluded that microbial accessibility to substrate, rather than chemical structure, is predominant in regulating soil organic matter decomposition. Our data show that DI resulted not only higher surface water content but also high DOC. If the elevated water content from DI increased R_A and R_S, then R_H would also increase due to the higher labile organic C that led to a net increase of CO₂ emissions compared to the SDI.

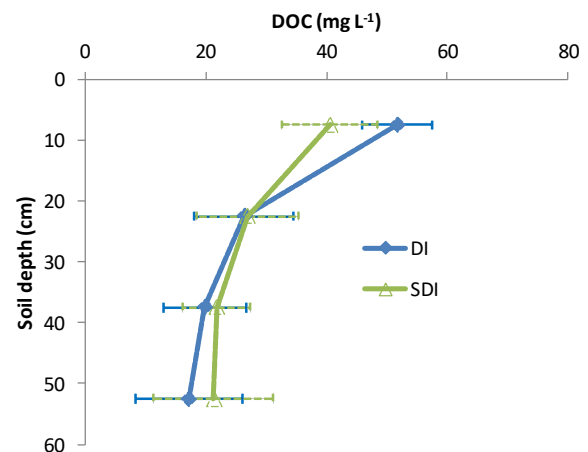


Fig. 9. Dissolved organic carbon (DOC) content in soil (1:1 soil/water ratio) that were collected at the end of growing season in pomegranate orchard. Error bars are 95% confidence intervals.

Although total CO₂ emissions from DI were not significantly higher from SDI in our study, we believe DI leads to generally higher emissions. Subsurface drip irrigation has tendency to yield lower CO₂ emissions as other studies have also shown the positive correlation between water content and CO₂ emissions [9], [10], [15]. Fewer studies have examined the difference between DI and SDI and evidence from Wei *et al.* [17] and our studies suggest generally lower greenhouse gas emissions from subsurface irrigation because of reduced N₂O emissions [25]. The SDI also led to higher water use efficiency and much lower weed pressure Ayars *et al.* [22] as well as higher N use efficiency Tirado-Corbal á *et al.* [24]. Thus, SDI provides generally more benefits than DI in water and nutrient management and mitigating greenhouse gas emissions.

IV. CONCLUSIONS

Field data collected from an irrigated pomegranate orchard illustrated that DI led to much higher CO₂ emission flux at the irrigation line compared to that from SDI with drip tubing installed at about 0.5 m depth below soil surface. The differences are attributed to soil water content that affect biological activities in surface soil. Although estimated cumulative emissions from the whole orchard were not significantly different due to relatively small wetting areas by drip irrigation, SDI provides more benefits by increasing

water and nutrient especially N use efficiency, potentially reducing chemical use because of lower weed populations, and reducing GHG emissions (N₂O and CO₂). Thus, SDI is still considered a promising efficient strategy for resource management and improvement on sustainability of crop production.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Dr. Gao led this research and drafted the manuscript. Ms. Hendratna, Dr. Cai, and Dr. Qin assisted data collection and processing. Mr. Pflaum helped data processing and edited the paper. Dr. Phene designed the experiment and maintained field operations.

ACKNOWLEDGMENT

We would like to express our appreciation for making field measurements by Mr. Robert Shenk and Mr. Mathew Brase, USDA, Agricultural Research Service, San Joaquin Valley Agricultural Sciences Center, Parlier, CA, USA 93648.

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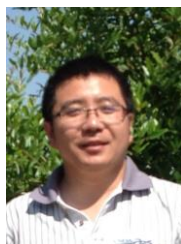


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