Subsurface Drip Irrigation Reduced Nitrous Oxide Emissions in a Pomegranate Orchard

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***Abstract*—Soil fertilization is one of the major sources for nitrous oxide (N_2O) emissions and soil moisture is among the most important factors affecting its production. Thus, one of the important mitigation strategies in semiarid or arid regions is through irrigation and/or fertigation management. The objective of this research was to evaluate the effects of different drip irrigation methods and N application levels on N_2O emissions. Nitrous oxide emission flux and N_2O concentration in soil profile were measured in a pomegranate field for two growing seasons under two irrigation systems [subsurface drip irrigation (SDI) at ~0.5 m depth and traditional surface drip irrigation (DI)], and three N application rates (50%, 100%, and 150% of current practice rate). Both years' data showed that N_2O emissions has a high and positive correlation with N fertilization events and application levels. Nitrous oxide emissions from DI at 100% and 150% N levels were over an order of magnitude higher compared to those from SDI based on the data of the first year. Data from the second year confirmed the first year's findings of high emissions from DI. A positive linear correlation between the N_2O emission flux and N_2O concentration in soil-gas phase was identified that supported emission data. This research demonstrated that although N fertilization is a major cause for N_2O emissions, subsurface drip irrigation/fertigation can lead to a significant emission reduction in addition to other benefits, such as increased water and nutrient use efficiencies, and reduced weed pressure.**

***Index Terms*—Chemical nitrogen fertilizer, greenhouse gas emission, high-frequency drip irrigation.**

I. Introduction

Nitrous oxide is a potent greenhouse gas (GHG) and has a global warming potential (GWP) 298 times that of an equivalent amount of carbon dioxide (CO_2) for a 100-year timescale [1]. Agricultural soils are estimated to contribute about 75% of the total U.S.A. N_2O emissions. Although N_2O emission accounts only for 5% of total GHG emissions, because of its high GWP and major source from agriculture, reducing N_2O emissions from agricultural fields plays an important role in mitigating global warming. Evaluation of field management practices (e.g., irrigation and fertilization) would assist in the development of mitigation strategies.

Soil water content is one of the most important factors affecting N_2O emissions. Nitrous oxide is produced primarily via microbial nitrification and denitrification processes. With increased soil water content, denitrification can become more significant and that led to much higher N_2O emissions [2], [3]. A number of studies have shown that N_2O emissions were related positively to irrigation or irrigation amount [4] and increased by increasing or higher water-filled pore space (WFPS) [5], Trost *et al.* [6]. In forest soils, N_2O emissions increased with increasing WFPS or decreasing water tension with the maximal N_2O emissions measured between 80 and 95% WFPS or 0 kPa water tension [7]. In arable lands, higher soil moisture showed over 100 times greater N_2O cumulative production at 70 WFPS than at 40 WFPS when studying cover-crop residue effects on N_2O emissions [8]. However, different irrigation system affects soil moisture distribution drastically in the field. Surface drip irrigation has been found to reduce N_2O emissions compared with flood irrigation [9], conventional furrow irrigation and side dress fertilization [10], and sprinkler or other irrigation systems [11]. Studies on effects of subsurface drip on GHG emissions are limited especially in orchards. Wei *et al.* [12] reported subsurface watering to saturate subsurface soil at 15–50 cm reduced N_2O emissions in soil boxes. Subsurface drip at 15 cm soil depth in a tomato field, however, did not reduce emissions [13]. In a cotton field with raised beds, Bronson *et al.* [14] reported that N_2O emissions ranged from 0.1–0.54%, 0.15–1.1%, and <0.1% of added N fertilizer for furrow, sprinkler, and subsurface drip irrigation (to 22–28 cm depth) systems, respectively. Maris *et al.* [15] did find SDI with drip tape 50 cm from tree trunks and at 20 cm soil depth reduced markedly N_2O emissions in an olive orchard. The results from SDI with water applied to shallow soil depth varied among studies.

California (CA), which is located in the south-west corner of the continental United States of America and adjacent to the Pacific Ocean, is the nation's top agricultural production state with approximately $47 billion output in 2015 [16]. The state's total value of all fruits and nuts was $18.1 billion, nearly 67% of the US total value of all fruits and nuts. Most of the tree fruits and nuts are produced in the San Joaquin Valley (SJV), one of the most productive regions in the world (annual agricultural output exceeding $30 billion). The climate in the SJV is Mediterranean with hot/dry summers and cool/moist winters. All crops in the SJV are irrigated

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during summer. Ever increasing water shortage has forced the region to consider more water efficiency strategies including improving irrigation technology and growing drought tolerant or less water demanding crops, such as pomegranate (*Punica granatum L.)*.

A field study was conducted from 2010–2015 in the SJV to determine basic water and nitrogen (N) requirement in a pomegranate orchard. The field treatments included two main irrigation treatments as surface drip irrigation (DI) and subsurface drip irrigation (SDI) and three N application rates as sub-treatments. The findings on treatment effects on yield, N requirement, and weed as well as C and N dynamics from this field research are reported in Ayars *et al.* [17] and Tirado-Corbalá *et al.* [18], respectively. Conclusions included that although yields were not significantly different between the two irrigation systems, SDI used less water with much lower weed pressure than DI. There was significantly higher N uptake in fruits from SDI at least in two out of the last three years of the study. The specific objective of this paper was to evaluate the effects of drip irrigation method and N application level on N_2O production or emissions. Data were collected from two consecutive years (2012–2013) after the pomegranate orchard was established in 2010. We hypothesize that higher surface soil water content from DI would lead to higher N_2O emissions than drier conditions from SDI.

II. Materials and Methods

A. Study Site, Treatments, and Field Operation

This research was conducted in a pomegranate orchard (1.4 ha) at the University of California, Kearney Agricultural Research and Extension Center, Parlier, CA on a Hanford sandy loam (coarse-loamy, mixed, superactive, nonacid, thermic Typic Xerorthents). The soil has a pH 7.5 (1:2 0.01 M $CaCl_2$); $EC_{25(1:1)}$ 171 µS cm^{-1}; and field capacity ~17%. The orchard was established in 2010 by planting pomegranate trees (*var. Wonderful*) and continued for five years. Detailed information about the field set up can be found in Ayars *et al.* [17]. Briefly, the field experiment included two main irrigation treatments: DI and SDI, and three sub-treatments N application rates of 50, 100, and 150% of current practice for a total six treatments in five replications (blocks) in a split-plot design. Each plot consisted of three tree rows with a row spacing of 4.9 m and each row had total 7 trees with a tree spacing of 3.6 m (total 567 trees ha^{-1}). All trees received uniform application of fertilizers during the first two years (2010–2011) of growth to ensure uniform stand prior to treatments. The different fertilization treatments started in 2012. For all treatments, fertilizers were applied through irrigation system (fertigation).

Two irrigation drip lines (laterals) (one on each side of the tree) were installed at a distance of 1.1 m from the row at soil surface for the DI and at soil depth of 50–55 cm for the SDI. Irrigation was applied after 1 mm of crop water use measured in a lysimeter located in the field, which resulted in high irrigation frequency (8–12 times per day during summer time). To compensate for higher evaporation loss, DI treatments received 10% more water than SDI starting in 2012. To investigate the moisture distribution pattern under the two irrigation systems, soil samples were collected on 6 August 2012 by sampling soils to 1 m depth at 20 cm increment and water content was determined using gravimetric method.

For N fertilization, N-pHURIC® 10/55 (urea and sulfuric acid with 10% N and 18% S) was applied through irrigation system to all N1, N2, and N3 treatments and to maintain irrigation water pH at 6.5 to avoid precipitation of phosphates. For the additional N requirement, ammonium nitrate (20% N or AN20) was injected to N2 and N3 treatments. For P and K supply, phosphoric acid (H_3PO_4) and potassium thiosulfate (25% K from K_2O and 17.5% S) were injected to all treatments at irrigation water concentrations of 15–20 mg L^{-1} for P and 50 mg L^{-1} for K (refer to Ayars *et al.* [17] for details). Fertilizer application began in late April or early May through August for both 2012 and 2013. Total N applied during the growing season was 52, 165 and 279 kg ha^{-1} for 2012, and 71, 166, and 244 kg ha^{-1} for 2013, in N1, N2, and N3 treatments, respectively. Nitrogen application schedule can be shown by the irrigation water N concentration in Fig. 1a and Fig. 1b for 2012, and 2013, respectively. In 2013, however, there was an interruption in fertilization for approximately one month starting in early June due to a pump failure, which resulted in no fertilizer application during this period of time for all treatments. Since the pump was repaired towards the end of the growing season, only small amounts of N were applied at similar rates to all treatment plots. Thus, N application among the three N levels were different only during the first month of the growing season in 2013.

B. Field Sampling and Analyses for N_2O Emissions and Production in Soil Profile

Nitrous oxide data were collected for all six treatments during both 2012 and 2013. One tree near the middle of a treatment plot (total 7 trees) was selected for field sampling. The first year's data were collected from one replicate due to lack of personnel for sampling in the large orchard. After significant differences between the treatments were observed, we decided to collect data for the second year from two treatment blocks to confirm the first year's findings. To further verify that the data collected were representative for evaluating the treatment effects, certain dates were selected for collecting data from three replicates when possible. Sampling during each year was conducted before irrigation/fertigation and continued through the growing season. The measurements were carried out between 9:00–12:00 for each day sampling. Thus, the flux data were suitable for evaluation of treatment effects rather than estimates for cumulative or total emissions.

Nitrous oxide emissions were measured using passive chamber method. Briefly, during N_2O sampling, the chamber was placed on a chamber base that was inserted into soil for approximate 5 cm depth. Upon closure of the chamber (i.e., by sealing the chamber top to the chamber base) 20 mL of gas inside the chamber were collected using gas-tight syringes every 30 min for up to 1.5 hours and during this period of time, a linear increase of N_2O concentration inside the chamber was observed upon closure. The sampling was done manually in 2012, but in 2013 an auto-sampler was used. The auto-sampler design, sampling protocol, laboratory analysis, and data processing for N_2O flux are described in Gao *et al.* [19]. Each gas sample was preserved by injecting into 10 mL glass headspace vials that were previously flushed with ultra-zero grade air to reduce background N_2O level. The N_2O concentration was analyzed on a gas chromatograph (6890N GC) using a headspace sampler (G1888), a HP-PLOT Q column, and a micro electron capture detector from Agilent Technologies (Santa Clara, CA, USA). Emission flux (f, μg m^{-2} h^{-1}) was calculated from the linear model:

$$f = \frac{VdC}{Adt} = bh$$

where dC/dt is the slope (b, μg N m^{-3} h^{-1}) of the linear equation by plotting N_2O concentration vs. time, and h is the effective chamber height (m), which is the ratio of the chamber volume (V, m^3) to the surface area (A, m^2) covered by the chamber. During measurement, the chamber base was inserted to the soil above the drip lines for SDI. For the DI treatment plots, the base was installed over the drip line by cutting the bottom half edge where the drip line ought to be and burying the drip line slightly below the base.

At the same location where the chamber was installed, stainless steel capillary tubes were installed near but outside of the chamber base at soil depths of 15, 30, 45, 60, and 100 cm. Sampling of the N_2O in the profile was done at the same time when the emission samples were collected. Sample preservation and analysis were the same as the emission samples.

C. Data Analysis

When data were measured from three replicates (e.g., N_2O emission measurements from selected dates; soil water content distribution), statistical analyses were conducted using SAS® software 9.4 [20]. A mixed model analysis was performed followed by mean separation using Tukey's adjustment at $P<0.05$.

III. Results and Discussion

A. N_2O Emissions

Results of the N_2O emission flux during 2012 and 2013 growing seasons in the pomegranate orchard are shown in Fig. 1. Both years' data clearly showed that chemical N fertilizer application during growing season caused significant increase in N_2O emission rates. Emissions were extremely low before fertilizer application started in spring and after fertilizer application stopped in the fall. Secondly, SDI resulted in much lower N_2O emissions than DI. In 2012, N2 and N3 treatments with DI resulted in the highest emissions (up to 800 μg m^{-2} h^{-1}). The lowest N application (N1) showed negligible emissions under DI. The N_2O emission rates from SDI plots were all below 10 μg N m^{-2} h^{-1} throughout the season regardless of N application rates. The data indicate that N_2O emission is indeed highly associated with N fertilization and significantly impacted by irrigation method. The results indicate N transformation from fertilization and high surface water content were the two factors leading to high N_2O emissions.

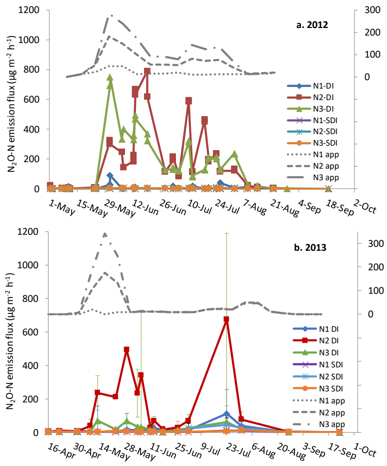

Fig. 1. Nitrous oxide emissions from a pomegranate field (a) 2012, (b) 2013. Treatments: DI=surface drip irrigation, SDI=subsurface irrigation, N1, N2, and N3=50% (N= 52–70 kg ha^{-1}), 100% (N=165–166 kg ha^{-1}), and150% (N=245–279 kg ha^{-1}) in 2012–2013 in reference to common practices. Error bars for 2013 data are standard deviations of the mean (n=2).

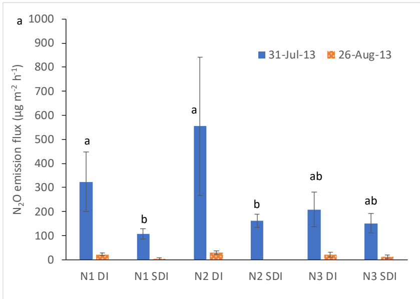

Fig. 2. Nitrous oxide emissions measured from three replicate plots on selected dates in 2013 in a pomegranate field. DI and SDI refer to surface drip and subsurface drip irrigation respectively; N1, N2, and N3 refer to N application at 50%, 100%, and 150% in reference to common practices. Error bars are standard error of the mean (n=3).

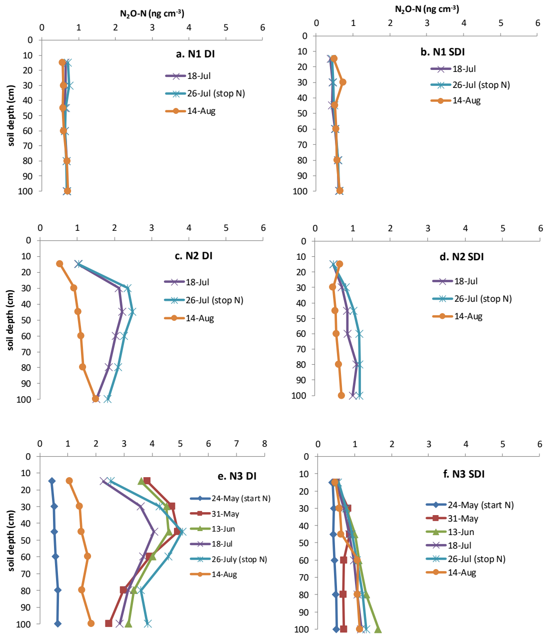

Fig. 3. Nitrous oxide concentration in soil gas-phase during 2012 growing season in a pomegranate field. DI and SDI refer to surface drip and subsurface drip irrigation respectively; N1, N2, and N3 refer to N application at 50%, 100%, and 150% in reference to common practices.

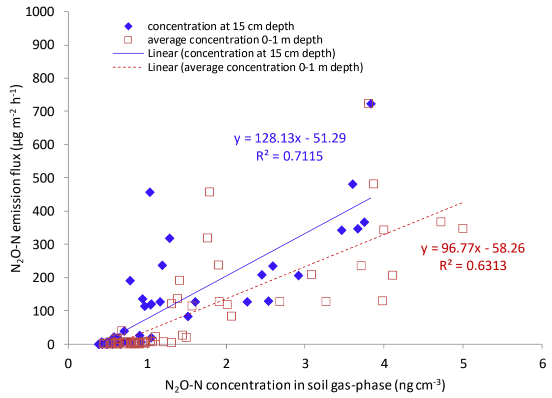

Fig. 4. Positive correlations between N_2O emission flux and N_2O concentration in soil gas-phase at either surface soil (15 cm depth) or average of soil profile (0–1 m).

In 2013, N_2O emission data showed high variability, but the higher emissions were consistently shown from DI with the highest from N2 treatment. The failure of pump that was controlling fertilization between late May and middle June caused low emission from all treatments during this period of time. Although the second peak emission rate in middle of July was from N2 DI, large variation was observed between the two replicates that must have been influenced by local soil moisture conditions and/or preexisting N conditions at the monitoring locations. The data generally show higher N_2O emission rates from higher N application rates under DI and the difference between N2 and N3 was not apparent. Higher emissions from DI than SDI indicate a significant shift in microbial communities that might have contributed to the highly variable N_2O emissions. Gaseous concentration data in soil (see section below) indicated that the monitoring location in N2 treatment had much higher N_2O productions. Overall, the data from the second year showed again that all SDI treatments had much lower N_2O emissions than those from DI. Measurements from three replicates at two selected times also showed that DI had significantly higher N_2O emission flux than that from SDI (Fig. 2) at least at two N application levels, which was consistent for the sampling dates. At both sampling dates, application of N was not different among the three N levels (Fig. 1b), thus the differences in the N_2O flux were mainly attributed to different irrigation methods. The no significant differences among all three N levels at either DI or SDI also support this conclusion.

B. N_2O Production in Soil and Correlation with Emission Flux

The N_2O concentration in soil profile was found to highly correlate with N_2O emission flux**.** Changes of N_2O concentrations in soil during the growing season in 2012 are shown in Fig. 3. Immediate sampling following the first fertilizer injection on May 24 showed low soil N_2O concentrations. Within a few days and continuous fertilization on 31st of May, much higher concentration was measured throughout the soil profile at the N3 level (Fig. 3 e,f). The concentrations then decreased with time until another fertilization. The last fertilizer application was on 26 of July when the highest N_2O concentrations in soil profile were measured in all treatments, but the concentrations were then drastically reduced by mid-August. In general, N_2O concentrations in soil were higher in DI plots compared to SDI at the same application rate except very little differences at the N1 rate.

Fig. 3 shows that the N_2O production in soil followed two different distribution patterns under the two irrigation methods. From DI, N_2O concentrations were higher (highest in N3 treatment) in surface soil (at 30 or 40 cm depth). The lower concentrations measured at 15 cm depth was due to faster physical transport through the soil-air interface to the atmosphere. The concentration decreased as the depth increased below the highest concentration. For the SDI, however, N_2O concentration was low in surface and tended to increase with soil depth. These were due to N application at surface for DI, but in subsurface for SDI. Tirado-Corbalá *et al.* [18] showed that dissolved organic carbon (DOC) and nitrate concentrations under the SDI were higher in subsurface soils (below 30 cm) than surface soil compared to those under DI with higher concentrations in upper soil depths. The data support that microbial reactions could occur in subsurface and explained why N_2O concentration could increase with soil depth in subsurface soil under SDI. However, Tirado-Corbalá *et al.* [18] also showed that the SDI soil at N1 and N2 levels did not result in elevated TN and NO_3^- concentrations at 105–120 cm soil depth suggesting reduced leaching risk using the high frequency irrigation. Both Ayars *et al.* [17] and Tirado-Corbalá *et al.* [18] have demonstrated that N3 treatment provided unnecessarily high N for the pomegranate demand. Overall, the lower soil N_2O concentration in SDI plots than that from DI may also be due to more efficient plant uptake. Tirado-Corbalá *et al.* [18] showed that total N uptake in fruits were significantly higher in SDI plots than that from DI at least for two out of three years. 2013 data (not shown) were similar to those collected in 2012 in distribution patterns except that the N3 treatment plots showed either lower or similar N_2O concentrations as the N2 treatment plots that were consistent with the emission data.

A positive correlation between N_2O emission flux and soil gas N_2O concentration is identified for both 2012 and 2013. Fig. 4 shows 2012 data by plotting emission flux vs both surface soil N_2O concentration and the average concentration in the soil profile (0–1 m depth). This positive correlation indicates that N_2O emissions from soil surface could be predicted from soil gaseous concentration in soil profile and soil physical properties that determine transport processes.

C. Mitigation of N_2O Emission through Irrigation and Fertilization Management

The field data indicate that high frequency SDI and fertigation can effectively reduce N_2O emissions in comparison with the conventional DI. At the same N application level, N_2O emission rates from DI were always much higher than SDI based on the two years' field measurement (Fig. 1). The higher emission rates from DI were attributed to the large differences in soil moisture condition in surface soil in addition to the N supply, i.e., the wet surface in DI and drier surface in SDI are one of the critical factors contributing to the differences in N_2O emissions. Wang *et al.* [21] reported that increased soil moisture stimulated the growth of ammonia-oxidizing bacteria and nitrite reducer (*nirK*) and total N_2O emissions were positively correlated to ammonia-oxidizing bacteria abundance. The SDI also resulted in higher water use efficiency and much lower weed pressure Ayars *et al.* [17] as well as higher N use efficiency Tirado-Corbal á*et al.* [18]. All the benefits plus the reduced N_2O emissions in this study make SDI preferable to the DI. Edwards *et al.* [13] did not find significant difference in N_2O emissions between SDI and DI from a tomato field because the drip tape in their study was buried at a much shallower depth (15 cm depth below the surface) compared to the ~50 cm depth in our study. They did illustrate that higher surface soil moisture from DI resulted in significantly higher seasonal CO_2 emissions than SDI. All data indicate that to reduce N_2O emissions, drip irrigation may need to be applied below a certain soil depth, which may vary among soil types or crop production systems, an area that needs further investigations.

The higher surface soil moisture and fertilizer application to surface soil from DI are the major causes for stimulated microbial activities that lead to much higher emissions in comparison with SDI. Applied N is subject to either nitrification or denitrification and through both N_2O can be produced and the process is highly correlated with oxygen (O_2) pressure or WFPS. Nitrification rates were reduced by a factor of 6–9 when O_2 decreased from 20.4 to 0.35 kPa.

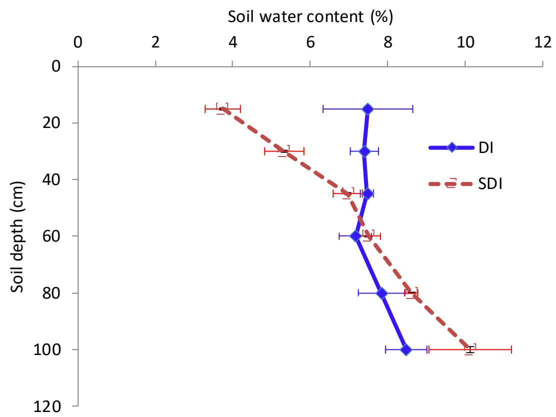

Fig. 5. Different distribution in soil water content between DI and SDI. Measurement was made on 6 August 2012, during the growing season.

Khalil *et al.* [2]. Many studies have observed the increased N_2O emissions as soil moisture or WFPS increased Dobbie *et al.* [5], Schindlbacher *et al.* [7], Trost *et al.* [6], and Pimentel *et al.* [8]. This relationship was further examined under well controlled conditions by Cai *et al.* [3] who found two distinctly different linear correlations between N_2O emission and soil nitrite (a precursor for N_2O) concentration with a much deeper slope for soil moisture above water holding capacity than that below. In the current study, significantly higher soil water content in DI than that from SDI in soil depth above 40 cm was determined (Fig. 5). All data suggest that drip tapes buried at certain depth to produce significantly drier condition in top 30 cm can reduce N_2O emissions.

Effective N management is another key to reducing N_2O emissions. Both N source and application rate have significant impact on N_2O production, thus can be managed to reduce N_2O emissions. An integrated system (drip irrigation, reduced tillage, and fertigation) has shown to significantly reduce N_2O emissions by >70% in comparison with the conventional (furrow irrigation and sidedress fertilizer injection) [10]. Under DI, fertilizer types also affect surface emissions of N_2O in an almond orchard, which were estimated as: high frequency irrigation or HF with urea and ammonium nitrate (UAN) > standard ($4 \times year^{-1}$) UAN > HF NO_3^- [22]. They also found that N_2O production was highest at 10–15 cm depth and reduced below 20 cm depth, which agrees with our observations (Fig. 2). Many studies, e.g., Lebender *et al.* [23], Cai *et al.* [3], have reported the emissions increase as N application increases. Applying N based on plant needs and avoiding excessive N supply in soil not only minimize N_2O emissions, but also reduce leaching and losses via other pathways. The worst scenario for N_2O emissions is the combination of high moisture and N application to surface soil. Thus, any practice that prevents high N input directly to surface soil and high moisture building-up would minimize N_2O emissions. These findings should apply to all irrigation systems regardless of crop types.

Although this research illustrated differences in N_2O emission flux between the DI and SDI systems in a pomegranate orchard, there are remaining questions or further investigations that are needed. We used both DI and SDI with HF irrigation in this study. As SDI technology has not been adopted in many places and DI is still used widely, the higher N_2O emissions from DI can be reduced by reduced irrigation frequency. From a two-year study, Fentabil *et al.* [24] showed that irrigation every 2nd day reduced area-scaled emissions by 27% compared to irrigation every day and mulching also reduced emissions by 19%. Using N transformation inhibitors e.g., Cai *et al.* [3], or controlled-release fertilizer, e.g., Braun and Bremer [4], has been reported to reduce emission in many studies. Also, we only measured emissions from drip lines close to the trees. There are significant spatial differences based on the distance from the drip tape or emitters in orchards. Pang *et al.* [25] showed that in addition to the seasonal pattern (high in hot-humid summer and low in cold-dry winter), annual average N_2O emissions were the highest at 0.5 m distance from trees in a non-irrigated apple orchard. In an irrigated orchard that is similar to our study conditions, relatively higher N_2O fluxes were frequently observed in tree rows compared to the tractor rows during growing seasons [26], [27]. These seasonal and spatial variations as well as fertilization, rainfall, and irrigation events must be taken into account to estimate total N_2O emissions and develop mitigation strategies in orchards. As many factors and processes are affecting N_2O emissions, integrative approaches, such as those outlined by Hatfield [28] should always be emphasized in management practices under specific environments.

IV. Conclusions

Two year's field data from the pomegranate orchard consistently demonstrated that high frequency SDI and fertigation at about 0.5 m depth below soil surface resulted in much lower N_2O emissions compared to the conventional DI.

Subsurface drip irrigation allows fertilizer and water application to deeper depth and the relatively drier soil surface reduces biological activities that led to low N_2O production with more efficient use of water and nutrients. With increasing shortage of water supply for agriculture, SDI provides a more resource efficient strategy in orchard management. The benefits to improve water/nutrient use efficiency and reducing weed pressure in orchards as well as reducing GHG emissions makes SDI a promising technology to enhance the long-term sustainability of irrigated agriculture. The findings are believed to be applicable to all irrigated agriculture.

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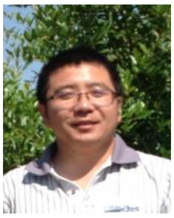

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