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Water-conscious management strategies reduce per-yield irrigation and soil emissions of CO_2, N_2O, and NO in high-temperature forage cropping systems

Holly M. Andrews[a,1,*], Peter M. Homyak[b], Patty Y. Oikawa[c], Jun Wang[d], G. Darrel Jenerette[e]

[a] Department of Evolution, Ecology, and Organismal Biology, University of California Riverside, 900 University Ave, Riverside, CA 92521, USA
[b] Department of Environmental Sciences, University of California Riverside, 900 University Ave, Riverside, CA 92521, USA
[c] Department of Earth and Environmental Sciences, California State University East Bay, Hayward, CA 94542, USA
[d] Department of Chemical and Biochemical Engineering, University of Iowa, Iowa City, IA 52242, USA
[e] Department of Botany and Plant Sciences, University of California Riverside, 900 University Ave, Riverside, CA 92521, USA

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ABSTRACT

Agricultural soils are important sources of greenhouse gases carbon dioxide (CO_2) and nitrous oxide (N_2O), as well as nitric oxide (NO), a precursor to tropospheric ozone. Management approaches that constrain these emissions can limit future warming and improve regional air quality, especially in high-temperature agroecosystems where soil emissions are high. Subsurface drip irrigation is a promising management solution that can limit emissions via targeted rhizosphere access to water and nitrogenous fertilizers. In complementary field studies in southern California, we compared per-yield irrigation and soil emissions in surface- and drip-irrigated field plots growing alfalfa (*Medicago sativa* L.) and sudangrass (*Sorghum bicolor* ssp. Sudanese), two forage crops with differing fertilizer requirements. For each study, we monitored soil temperature, moisture, and emission responses to irrigation in both spring and summer using a custom automated chamber array that recorded measurements every 30 minutes. We found that, compared to furrow irrigation, drip irrigation in sudangrass increased hay yield by 6% and per-yield soil CO_2 emissions by 9% while it decreased irrigation demand by 49%, N_2O emissions by 59%, and NO by 49%. In alfalfa, drip irrigation increased yield by 7% while decreasing irrigation by 1%, per-yield soil CO_2 emissions by 59%, N_2O by 38%, and NO by 20%. In both crops, differences between irrigation types were strongest in summer months, when high temperatures produced large pulses of N_2O and NO in sudangrass and CO_2 in alfalfa following flood irrigation relative to small pulses following drip irrigation. As agriculture intensifies in warmer climates, implementation of subsurface drip irrigation can help reduce the emission of soil emissions that affect Earth's climate and regional air quality.

1. Introduction

Agricultural lands produce a large portion of annual soil emissions of carbon (C) and nitrogen (N) trace gases (Aneja et al., 2009), some of which contribute to climate forcing and others which degrade local and regional air quality (Sha et al., 2021; Wang et al., 2021). In the United States, agriculture is responsible for an estimated 12% of the national annual emissions of carbon dioxide (CO_2), the dominant biogenic greenhouse gas, and 51% of annual emissions of nitrous oxide (N_2O), a greenhouse gas with almost 300 times the warming potential of CO_2 (Davidson and Kanter, 2014; EPA, 2020; IPCC, 2019). Agricultural soils are also a major source of ozone-forming nitric oxide (NO) (Almaraz et al., 2018; Davidson and Kingerlee, 1997; Sha et al., 2021), particularly in fields that are fertilized with N (Davidson, 2009) and that are located in high-temperature regions (Oikawa et al., 2015; Wang et al., 2021). Trace gas emissions from soil are generally contingent on water availability; re-wetting dry soils can trigger metabolic pulses that extend to gaseous release, particularly if the transition from dry to wet is abrupt as occurs with traditional flood irrigation (Almaraz et al., 2018; Davidson et al., 2000). Following re-wetting, the magnitude and duration of emission pulses can also be modulated by interactions between temperature and nutrient availability, with the strongest pulses

* Corresponding author.
E-mail address: hollyandrews@arizona.edu (H.M. Andrews).
[1] Present affiliation: School of Natural Resources and the Environment, University of Arizona, Tucson, AZ 85721, USA.

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occurring in hot, nutrient-saturated soils (Leon et al., 2014; Liang et al., 2016; Oikawa et al., 2015). Increasingly, much interest is directed toward reducing agricultural contributions to climate change and air quality (Sanz-Cobena et al., 2017), and the links between irrigation systems and soil trace gas emissions are an important source of uncertainty and opportunity.

Because irrigation can trigger large trace gas emission pulses (Birch, 1958), soil emissions may be constrained with proper irrigation management. Most high-temperature agricultural fields are irrigated with surface flood irrigation despite evaporative losses sometimes exceeding 50% of irrigation inputs (Lu et al., 2017). To reduce water losses, subsurface drip irrigation has become a popular alternative (Velasco-Muñoz et al., 2019) since drip lines inject water directly into the plant rhizosphere, reducing water use and, presumably, pulsed soil C and N emissions. For example, evidence from vegetable and nut crops suggests drip irrigation reduces emission of CO_2 (Wei et al., 2021) and N_2O (Deng et al., 2018b; Kallenbach et al., 2010; Kuang et al., 2021; Suddick et al., 2011), but the effects on NO emissions are less conclusive with studies reporting no change (Sánchez-Martín et al., 2010) or only modest reductions (Sánchez-Martín et al., 2008). Therefore, the potential for drip irrigation to reduce trace gas emissions from high-temperature agroecosystems remains unclear and could depend on gas species of interest or other environmental factors.

Whether drip irrigation has potential to reduce soil trace gas emissions may depend on crop nutrient acquisition strategies or on the timing of irrigation over the plant growing season (Garland et al., 2014). Forage crops, popular in high-temperature regions, generally require N fertilizer together with irrigation—known as fertigation— to produce competitive yields, but such practices can produce substantial N loss via hydrologic and gaseous pathways (Davidson, 2009; Liu and Greaver, 2009; Suddick et al., 2011; Yan et al., 2005). Alternatively, cropping practices that use biogenic N fixation represent a more consistent way of adding N relative to fertigation, since N is not applied with water as pulses that can generate substantial N loss (Bøckman, 1997; Signor and Cerri, 2013). Beyond crop differences, relationships between irrigation and soil emissions may also be modulated by seasonal temperature (Sihi et al., 2020; Wei et al., 2021; Zhao et al., 2020) and wetting history (Oikawa et al., 2014); as such, differences in irrigation strategy effectiveness could be magnified in summer when air is hot and dry. Whether crop-specific water-nutrient interactions translate to reduced gaseous losses from high-temperature forage soils is not well understood and may differ between crops and across seasons. To address uncertainties in the effects of drip irrigation on soil trace gas emissions, we asked the overarching question: how do two contrasting irrigation systems, traditional surface flood irrigation and water-conscious subsurface drip irrigation, affect crop yield, water usage, and emissions of CO_2, N_2O, and NO?

To answer this question, we conducted field experiments in California's Imperial Valley, USA, an extensively cultivated, high-temperature region that serves as a model for future agriculture under climate warming projections (IPCC, 2019; Putnam and Kallenbach, 1997). In each study, we compared soil trace gas emissions following flood and drip irrigation using a custom array of automated soil chambers installed in fields growing either fertigated sudangrass (*Sorghum bicolor* spp. Sudanese) or N-fixing alfalfa (*Medicago sativa* L.), two crops with contrasting N acquisition strategies. We tested the prediction that management strategies incorporating drip irrigation would produce smaller per-yield emissions of CO_2, N_2O, and NO, compared to those produced by flooding, while also increasing water-use efficiency and maintaining consistent crop yield. We predicted that drip irrigation would be most beneficial in summer sudangrass since this treatment combination requires fertilization when background soil temperatures are likely highest. Our assessments of subsurface drip irrigation in crop-dependent and seasonal contexts can help improve understanding of mechanisms driving trace gas emissions from high-temperature agriculture and explore potential benefits of water-conserving infrastructure for a warmer world.

2. Methods

2.1. Study site and focal species

All measurements were made in experimental agricultural fields at the University of California Desert Research and Extension Center (DREC; https://drec.ucanr.edu/), located in Holtville, Imperial County, CA (32°N 480 42.6, 115°W 260 37.5, −18 m ASL elevation). Soils are mapped within the Imperial-Glenbar soil series, and are classified as Fine-silty, mixed, superactive, calcareous, hyperthermic Typic Torrifluvents (Imperial series) and Fine, smectitic, calcareous, hyperthermic Vertic Torrifluvents (Glenbar series; Soil Survey Staff, 2022). The soil texture is 42% clay, 41% silt, and 16% sand, with average pH of 8.3 and C and N content of 2.34% and 0.13%, respectively (Oikawa et al., 2015). DREC experiences a Mediterranean climate, with hot (mean high/low: 41 °C/25 °C) summers and mild (mean high/low: 22 °C/7 °C) winters (based on data from California Irrigation Management Information System). Experimental fields at DREC have been active since 1912 and are models for studying alternative irrigation strategies for desert forage (Grismer and Bali, 2001; Zaccaria et al., 2017). Previous work from this site has reported high trace gas emissions from soils (Eberwein et al., 2015; Liang et al., 2016; Oikawa et al., 2014, 2015).

For each crop study, we used two adjacent 0.08-ha fields, separated by a 15-meter strip of bare soil, as experimental testbeds to evaluate irrigation systems (Fig. 1). One field was irrigated by a gravity-fed surface irrigation system ("flood" treatment), the most prevalent irrigation practice in the region. The other field was irrigated via subsurface rubber drip tape ("drip" treatment) system installed underneath crop rows; drip lines with 36-cm spacing between emitters were installed at 1.5-meter separation (coinciding with spacing of rows) and 10 to 15 cm depth below the soil surface. These contrasting systems are directly associated with differences in location of irrigation in the soil profile, amount of water applied, and fertilization applications. Fields were additionally modified and managed according to conventional practices for each focal crop and irrigation system.

Two widely cultivated crops employing contrasting models in N acquisition strategy served as case studies to test our hypotheses: alfalfa (*Medicago sativa* L.) and sudangrass (*Sorghum bicolor* spp. Sudanese). Alfalfa is the largest forage crop commodity for Imperial County, grown on 62,795 ha (155,171 acres) (Ortiz, 2018); as an N-fixing legume, this

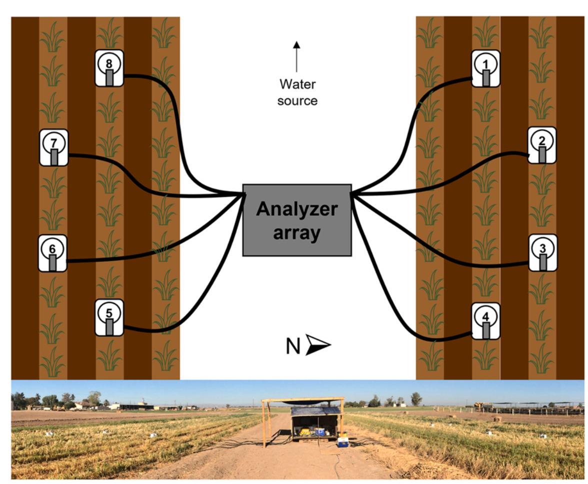

Fig. 1. Experimental design for each trace gas measurement campaign. Automated chambers were installed in a paired design in two adjacent 0.8-ha fields containing a focal crop species. Irrigation was manipulated at the field scale; one field received surface flood irrigation, while the other received subsurface drip irrigation. All eight chambers were measured on a 30-minute cycle.

crop is generally not amended with fertilizers. Sudangrass, a high-biomass-producing grass, is the third most prevalent forage crop in the Imperial Valley, encompassing 21,675 ha (53,562 acres) (Ortiz, 2018). Sudangrass generally receives a large fertilizer application at planting (100–150 kg N ha^{-1}) followed by smaller applications (50 kg N ha^{-1}) throughout the growing season (Meister, 2004; Oikawa et al., 2015). Studies in alfalfa have indicated the potential for drip irrigation to improve yield, save water, and retain soil nutrients (Fu et al., 2021; Zaccaria et al., 2017); sudangrass has received less research attention for irrigation improvements (Grismer and Bali, 2001). In a case study for each focal crop, we tested trace gas emission, water use, and yield impacts of irrigation management systems during spring and summer seasons.

2.2. Sudangrass case study: field set-up and management

Sudangrass was grown in 2018 using a fertigated furrow system (beds positioned 1.5 m apart with a 20-cm deep furrow between each bed). As common practice, drip and flood fertigation (simultaneous addition of fertilizer and irrigation) management systems tend to differ in both amount and type of fertilizer; to measure the impacts of these strategies in a relevant way for growers, we used the most common fertilizer-irrigation combinations for Imperial County. In flood-irrigated fields, fertigation consisted of large, single-event additions of anhydrous ammonia (NH_3) to furrows. Conversely, fertigation in drip-irrigated fields consisted of multiple, smaller additions of urea ammonium nitrate (UN-32) via drip lines within crop beds. While these two fertilizers differ in their components, they both incorporate quickly into soils and increase NH_4^+ and NO_3^- available to be lost as N_2O and/or NO.

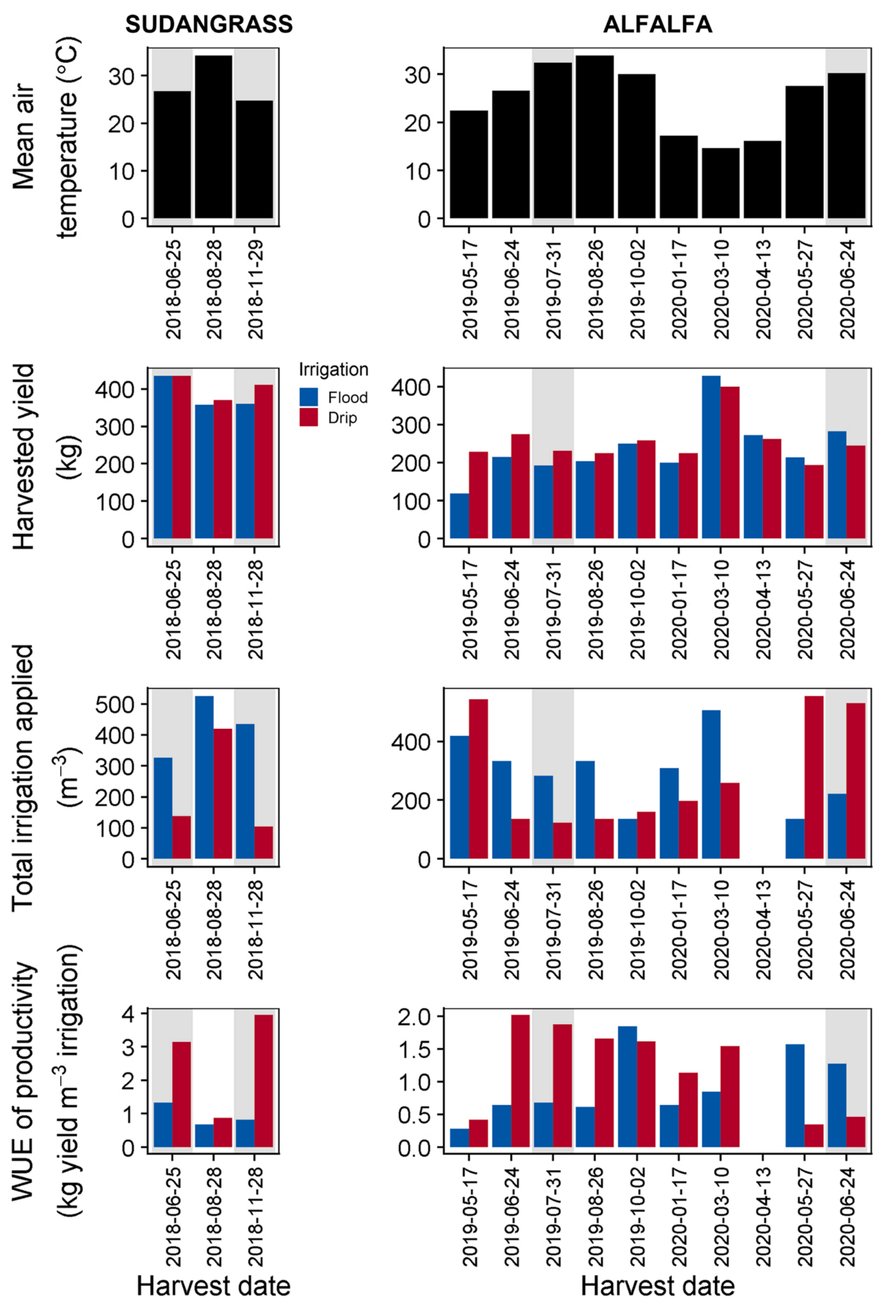

Fig. 2. Field-scale harvest metrics for each 0.8-ha field during sudangrass and alfalfa studies. Grey boxes indicate harvests where soil trace gases were also measured. Water use of productivity (WUE) was calculated by dividing yield harvested from each field by total irrigation applied during the harvest period. Air temperature and precipitation data were collected from CIMIS (https://cimis.water.ca.gov/Default.aspx).

On April 17, 2018, sudangrass seeds were planted and received initial irrigation; during each of three harvests (Fig. 2), aboveground biomass was clipped, leaving roots and the base of the stem intact. Flood-irrigated fields were fertigated with 100 kg N ha^{-1} on April 18 (Harvest 1) and September 7 (Harvest 3); drip-irrigated fields were fertigated with 25 kg N ha^{-1} on April 18, May 4, and May 17 (Harvest 1), as well as September 7 and October 5 (Harvest 3). Irrigation was applied when average soil moisture dropped below 10% in either field and generally occurred at 12- to 16-day intervals. We measured soil emissions in the first harvest period (April 16-May 21, 2018) and the third, final harvest period (August 28 to September 25, 2018). The only water that fields received during our emissions measurements was as irrigation; during the final harvest, fields received rain after our gas measurements had finished.

2.3. Alfalfa case study: field set-up and management

Alfalfa was grown in 2019–2020 using a flooding system without added fertilizers. In 2019, the same fields which we used for the sudangrass experiment were tilled and furrows filled in. Alfalfa was planted on March 15, 2019; hay was harvested on May 17, June 24, July 31, August 26, and October 12. As a perennial crop, alfalfa continued to be harvested in 2020 on January 17, March 10, April 13, May 27, and June 24. Irrigation was applied when average soil moisture dropped below 10% in either field and occurred in 2- to 30-day intervals depending on seasonal precipitation. We measured soil emissions during the third (June 26-July 14, 2019) and tenth (May 29-June 27, 2020) harvest periods. The only water that fields received during our emissions measurements was as irrigation; however, fields experienced unusually high precipitation in March-April 2020 prior to our measurements in May-June (Fig. 2). During the tenth harvest period, a damaged water pipe caused small, additional increases in irrigation rates in both fields.

2.4. Soil sampling for extractable nitrogen

For each set of emissions measurements, we collected 5-cm^2 x 10-cm deep soil cores from rows/beds adjacent to each soil collar at timepoints prior to and following the first irrigation event to track changes in extractable N (ammonium NH_4^+ and the sum of nitrite+nitrate NO_2^- + NO_3^-). In sudangrass, we collected cores at 0, 1, and 3 days post-irrigation; in spring, we collected additional cores at 2 and 10 days post-wetting and in summer we collected cores at 5 and 7 days. In alfalfa, we collected cores at 0 and 2 or 4 days post-irrigation to capture changes in soil N resulting from irrigation. Each core was homogenized, transported to the lab on ice, and extracted in 1:10 soil weight:solution volume ratio of 2 M KCl solution following standardized methods for inorganic N analysis (Carter and Gregorich, 2006). Extracts were shaken for 1 h, centrifuged, and gravity-filtered through 11-micron filter paper at room temperature followed by analysis via phenate method for ammonium and via acidification and automated cadmium coil reduction for nitrate and nitrite (Seal Analytical Inc., AQ2 Discrete Analyzer; Mequon, Wisconsin).

2.5. Soil temperature, moisture, and trace gas measurements

At the beginning of each study, four polyvinyl chloride (PVC) soil collars (20-cm diameter) were installed in each field (n = 8 collars total per study); each collar had a positionally-paired collar in the adjacent field to control for distance from irrigation pipes (Fig. 1). Collars were positioned on crop beds in between plants and pushed into the ground to 5-cm depth. An automated long-term chamber (LI-8100–104; LI-COR Bioscience, Lincoln, NE, USA) was fitted on each soil collar, and accompanying 5-cm soil temperature (LI-8150–203 thermistor probe; LI-COR Bioscience, Lincoln, NE, USA) and moisture (LI-GS1 probe; LI-COR Bioscience, Lincoln, NE, USA) probes were inserted into bed soils outside of, but adjacent to, collars. Although these probes were shallow compared to drip lines, percolation models suggest drip irrigation at our site can saturate soils up to 10 cm above emitter depth relatively quickly (Reyes-Esteves and Slack, 2019). All eight automated chambers were connected to a custom trace gas analyzer array housed inside an insulated, air-conditioned shed positioned between the two fields.

The measurement procedure for each chamber included a 30-second pre-measurement purge, a 2.5-minute active measurement period for trace gas concentrations and soil temperature and moisture status, and a 30-second post-measurement purge before cycling to the next chamber. Inactive chambers remained open and away from collars to minimize interference with soil-atmosphere exchanges; during active measurement, a chamber swiveled and closed over the collar to form a seal. Air collected from an actively-measuring chamber was passed through a multiplexer (LI-8150; LI-COR Bioscience, Lincoln, NE, USA) followed by a sequence of three trace gas analyzers: 1) a N_2O/CO cavity-ringdown infrared analyzer (Los Gatos Research, San Jose, CA, USA); 2) a CO_2 infrared gas analyzer system (LI-8100A; LI-COR Bioscience, Lincoln, NE, USA); and 3) a coupled nitrogen dioxide (NO_2) converter and NO monitor (Model 401/410, 2B Technologies, Boulder, CO, USA). Instruments had been previously calibrated using known concentrations of trace gas of interest. The multiplexer, N_2O/CO analyzer, and the CO_2 system formed a closed loop that returned sample air to the active chamber which was sealed over the soil collar; however, the NO_2/NO monitor is an open system, so a portion of air was siphoned from the sample loop through a one-way check valve and was measured as NO (and NO_2). By incorporating an NO "leak" in the sample loop, a small amount of error was introduced into flux calculations due to dilution of trace gas concentrations as in previous uses of closed chamber systems (Andrews and Jenerette, 2020; Davidson, 2000; Davidson et al., 2008); however, we assume this error to be small given the chamber volume and short measurement time. Concentrations of CO_2, N_2O, and NO were measured simultaneously every 1, 1, and 10 s, respectively. A complete measurement cycle through all eight chambers took place every 30 min and was controlled by the LI-8100A.

2.6. Data processing

Harvested biomass and irrigation data were collected at field scale; for these variables, we calculated water use efficiency (WUE) of productivity by dividing harvested dry biomass by total irrigation applied per field per harvest. We batch processed instantaneous soil flux, temperature, and moisture data for each emissions collection campaign using methods adapted from Andrews and Jenerette (2020). Instantaneous fluxes of CO_2, N_2O, and NO were calculated as the regression coefficient of linear increase in gas concentration during the 2.5-minute active measurement period, corrected for soil collar dimensions and atmospheric parameters following the Ideal Gas Law (Davidson et al., 2000). Soil temperature and moisture were averaged over this same period as well. Instantaneous fluxes of each gas were compiled and integrated with instantaneous soil temperature and moisture measurements at 30-minute resolution using a publicly-accessible R script (Andrews and Krichels, 2021). Logistical constraints for trace gas measurements forced a decision to not replicate treatments but allowed us to measure high resolution emission trajectories with replication across different field rows. With time series of these high-resolution measurements, we could interpret interactive responses to rapid changes in soil conditions, such as during re-wetting, that could be missed or misinterpreted at coarser temporal scales. We extracted the magnitude and timing of each peak flux and climate parameter, calculated as the maximum instantaneous measurement recorded over an irrigation event. We also extracted per-irrigation mean temperature, moisture, and daily emission values, the latter of which were calculated as the integrated area under each time series curve using linear trapezoidal method divided by the duration of time following the irrigation event and prior to the next one.

To link soil emissions to field-scale irrigation and yield measurements, we extracted per-yield emissions values for each trace gas and field. We multiplied each chamber's mean per-irrigation daily emissions by the length of each harvest period to calculation each chamber's per-harvest emissions. We then divided this per-harvest emission estimate by per-area yield to calculate the amount of each trace gas emitted per amount yield as estimated by each chamber. These calculations are similar to those used to estimate greenhouse gas intensity (GHGI), a measure which has been used to evaluate the global warming impact of irrigation in agriculture (McGill et al., 2018). Representing emissions in this way allowed us to compare the effectiveness of drip irrigation across time and between crops by taking into account differences in harvest cycles and plant physiological differences.

2.7. Statistical analyses

At field scale and for each crop, we tested individual effects of season (spring vs. summer) and irrigation type (flood vs. drip), without interaction terms, for predicting WUE using 2-way analysis of variance (ANOVA) and post-hoc t-tests. We also used repeated-measures ANOVA to test season and irrigation combinations, including interactions, for predicting soil extractable NH_4^+ and NO_3^-. We assessed effects of season, irrigation type, and irrigation number (1 vs. 2) on per-irrigation daily average soil temperature, moisture, and emissions for each focal crop by constructing a mixed effects model for each response of interest, with chamber number as a random variable. Distributions of trace gas data were non-normal and were log-transformed prior to model construction. We tested all combinations of season, irrigation number, and irrigation type using 3-way ANOVA and post-hoc Tukey's HSD tests and selected reduced models with the lowest Akaike Information Criterion (AICc).

3. Results

3.1. Sudangrass field results

In sudangrass, soil temperatures ranged between 8 and 42 °C. Following irrigation, flood chambers reached soil moisture levels up to 40% higher than drip chambers but dried more quickly. Water use efficiency (WUE) of productivity for sudangrass was 2.4 times higher in drip irrigation compared to flood during the spring; this difference increased to 4.8 times higher in the summer when the flood field produced lower yield despite much higher irrigation rates (Fig. 2). Soil extractable NH_4^+ was highest in spring, particularly in the flood treatment (Season*Irrigation $p = 0.01$); conversely, extractable NO_3^- did not differ across irrigation treatments ($p = 0.63$) but was highest in the summer ($p = 0.003$), reaching concentrations up to three times higher than for spring. Both N species peaked 2–3 days post-irrigation, suggesting similar infiltration times across fertigation treatments and seasons (Fig. 3).

CO_2 fluxes ranged from near-zero to 991 μg CO_2-C m^{-2} s^{-1} in all sudangrass measurements, with high heterogeneity across chambers (Fig. 4). Fluxes were suppressed immediately by irrigation followed by a delayed pulse at ~8 days. Flood-irrigated chambers produced more consistent CO_2 fluxes through time while experiencing a larger range of soil moisture (7–59%). Conversely, drip-irrigated chambers experienced stronger post-irrigation suppression of CO_2 followed by larger CO_2 pulses than in flood plots, while experiencing a soil moisture range (7–32%) almost half that in flood plots (Fig. 5).

N_2O fluxes ranged from near-zero to 3.53 μg N_2O-N m^{-2} s^{-1} in all sudangrass measurements. N_2O pulses occurred almost simultaneously with CO_2 suppression and dissipated by 4 days post-irrigation (Fig. 4). NO fluxes ranged from near-zero to 893 ng NO-N m^{-2} s^{-1} (Fig. 4) and followed N_2O pulses, occurring between 50 and 300 h post-irrigation. NO pulses were greater in flood- than drip-irrigated plots, particularly in summer months, and experienced strong diel fluctuations.

3.2. Alfalfa yield, irrigation, extractable N, and soil gas pulses

In alfalfa, soils experienced temperatures ranging 1 to 47 °C. Both irrigation treatments experienced similar maximum soil moisture levels but flood plots experienced more complete soil drying and therefore a larger soil moisture range (10–57%) than drip plots (19–58%). WUE of productivity for alfalfa was 2.7 times higher in drip irrigation compared to flood during Summer 2019; however, drip irrigation shifted to 2.8 times less efficient than flood in Spring 2020 (Fig. 2). Soil extractable NH_4^+ was generally higher in drip compared to flood chambers and increased following irrigation in summer compared to post-irrigation decreases in spring, particularly in drip (Fig. 3). Extractable NO_3^- was higher in flood chambers in the summer, but higher in drip in the spring (Season*Type $p = 0.002$); however, across all treatment combinations, NO_3^- decreased in response to irrigation (Fig. 3).

CO_2 fluxes ranged from near-zero to 862 μg CO_2-C m^{-2} s^{-1} in alfalfa, with high heterogeneity across chambers (Fig. 5). CO_2 fluxes were generally suppressed for longer and at lower magnitudes than for sudangrass, particularly in drip irrigation plots. N_2O fluxes ranged from near-zero to 2.76 μg N_2O-N m^{-2} s^{-1}, and NO fluxes ranged from near-zero to 88.2 ng NO-N m^{-2} s^{-1}; the timing of these pulses was

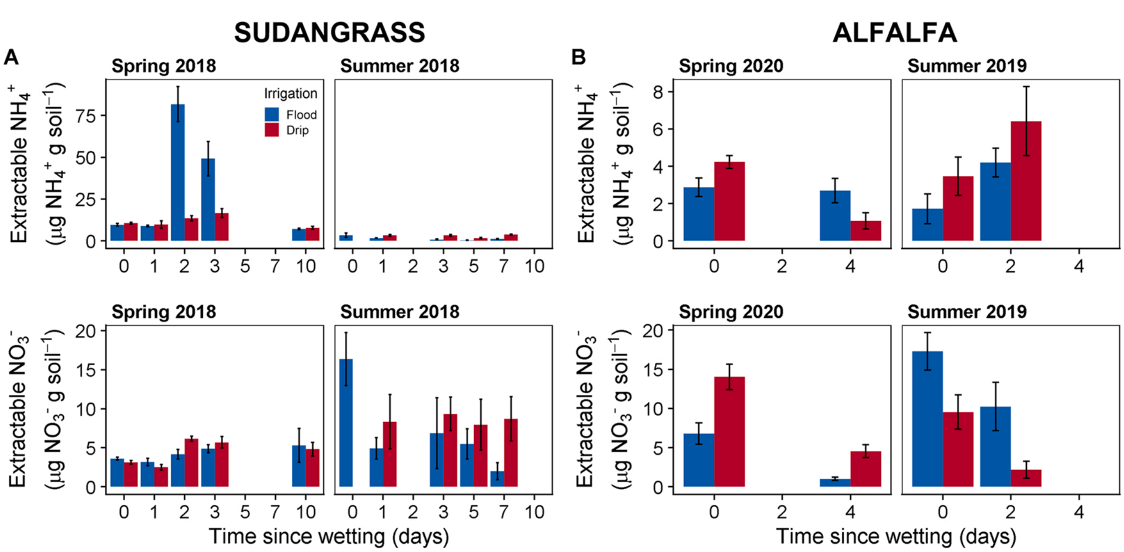

Fig. 3. Extractable NH_4^+ and the sum of NO_2^- and NO_3^- in the top 10 cm of soils following soil irrigation. Points and error bars indicate means and standard errors of extractable soil N at time points following irrigation. Colors delineate irrigation type.

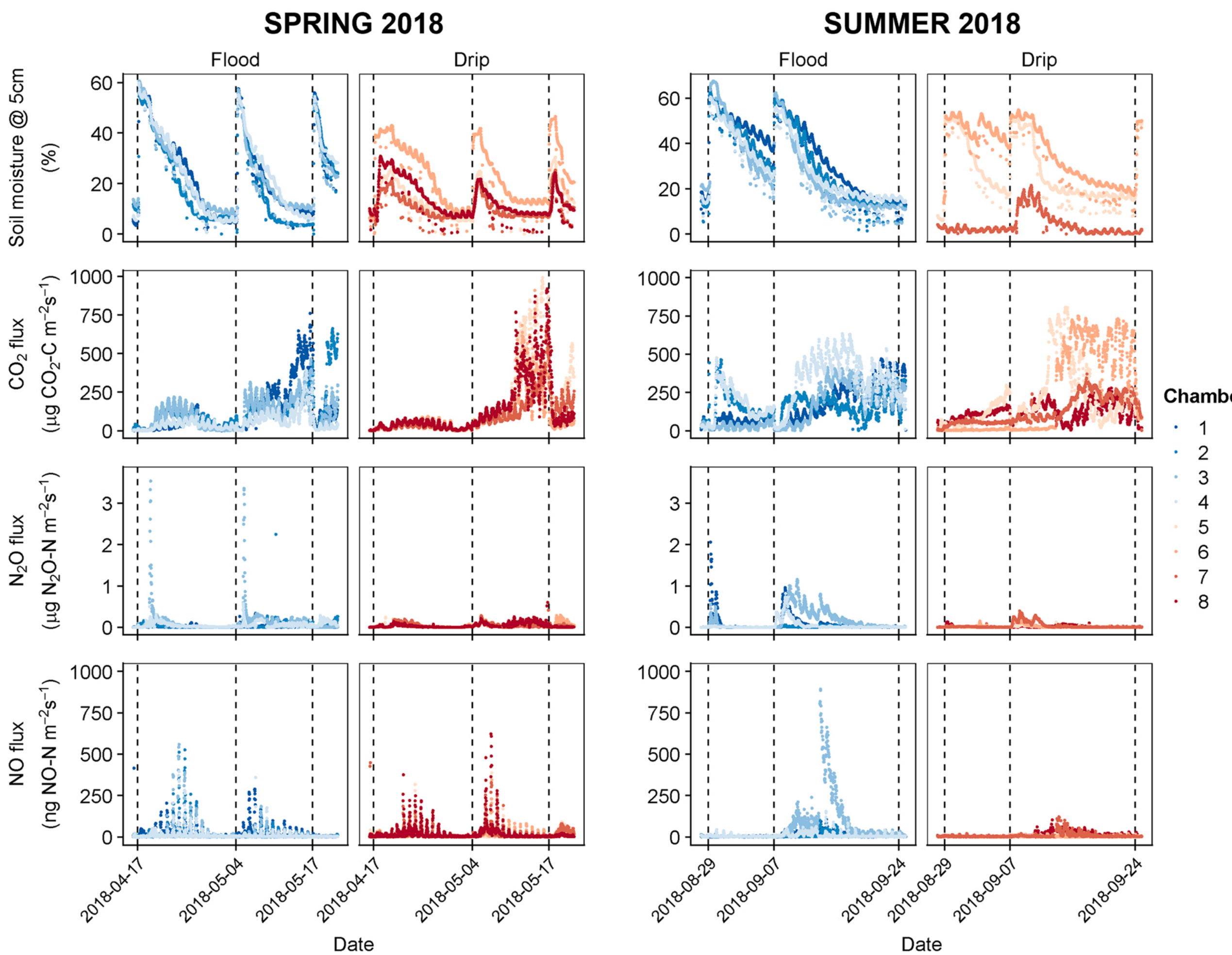

Fig. 4. Instantaneous soil moisture, carbon dioxide (CO_2), nitrous oxide (N_2O), and nitric oxide (NO) fluxes measured in sudangrass. Four chambers were installed in each irrigation treatment. Flood-irrigated chambers are colored blue and drip-irrigated chambers are colored red; individual chambers are delineated by color saturation. Dotted vertical lines delineate scheduled irrigation events within each campaign.

consistent with sudangrass, producing rapid N_2O pulses followed by delayed and longer NO pulses (Fig. 5). N_2O was the predominant N gas emissions from alfalfa fields, and pulsed emissions were larger in flood than drip treatments and during the spring compared to summer (Fig. 5).

3.3. Mean daily soil emissions responses to season and irrigation type and number

In sudangrass, mean soil temperatures increased throughout the spring and peaked in the summer (Season*Number $p < 0.001$), particularly in the drip field (Fig. 6, Supplementary material). Mean soil moisture was highest during the first irrigation of the summer campaign (Season*Number $p = 0.49$) but was also highly variable in drip chambers compared to flood. While irrigation treatments were not significantly different, moisture trended higher in flood chambers by up to 10%. Mean daily CO_2 fluxes were predominantly explained by irrigation number, where emissions were stronger during the second irrigation compared to the first. Irrigation type also contributed to CO_2 fluxes in a marginal time-dependent interaction ($p = 0.10$): drip chambers suppressed CO_2 fluxes in the first irrigation event but over-produced CO_2 during the second event compared to flood chambers (Fig. 6). Mean daily N_2O fluxes also tended to increase with subsequent irrigations, but increases were less pronounced in drip-irrigated chambers compared to flood. Alternatively, mean daily NO fluxes responded inconsistently to treatment groups (Season*Number*Type $p = 0.04$) but tended to be highest in spring rather than summer and most consistent in drip chambers compared to larger changes in flood chambers through time.

Alfalfa experienced similar increases in soil temperature over seasons and irrigations but increases were consistent in both fields and seasonal differences were smaller than for sudangrass (Fig. 6). Mean soil moisture differed by as much as 30% between seasons, particularly during each season's second irrigation event (Season*Number $p < 0.001$). Drip irrigation was more consistent across irrigations and seasons as well compared to spring lows and summer highs in flood chambers (Season*Type $p < 0.001$). Mean daily CO_2 fluxes were lower from drip-irrigated chambers compared to flood, with particularly strong reductions in the summer harvest (Season*Type $p < 0.001$); in contrast to trends in sudangrass, CO_2 fluxes decreased during second irrigation events compared to firsts. Mean daily N_2O fluxes experienced seasonally-dependent responses to irrigation: summer produced significant effects of irrigation type, with stronger emissions from flood chambers (Season*Type $p = 0.02$); alternatively, effects of multiple irrigations were strong in spring, where emissions were much lower following the second irrigation compared to first (Season*Number $p < 0.001$). Mean daily NO fluxes produced similar trends in irrigation effects to those of N_2O, but fluxes were overall higher in summer rather than spring (Fig. 6).

4. Discussion

In this study, we provide some of the first high temporal resolution emission trajectories following irrigation in forage crop systems.

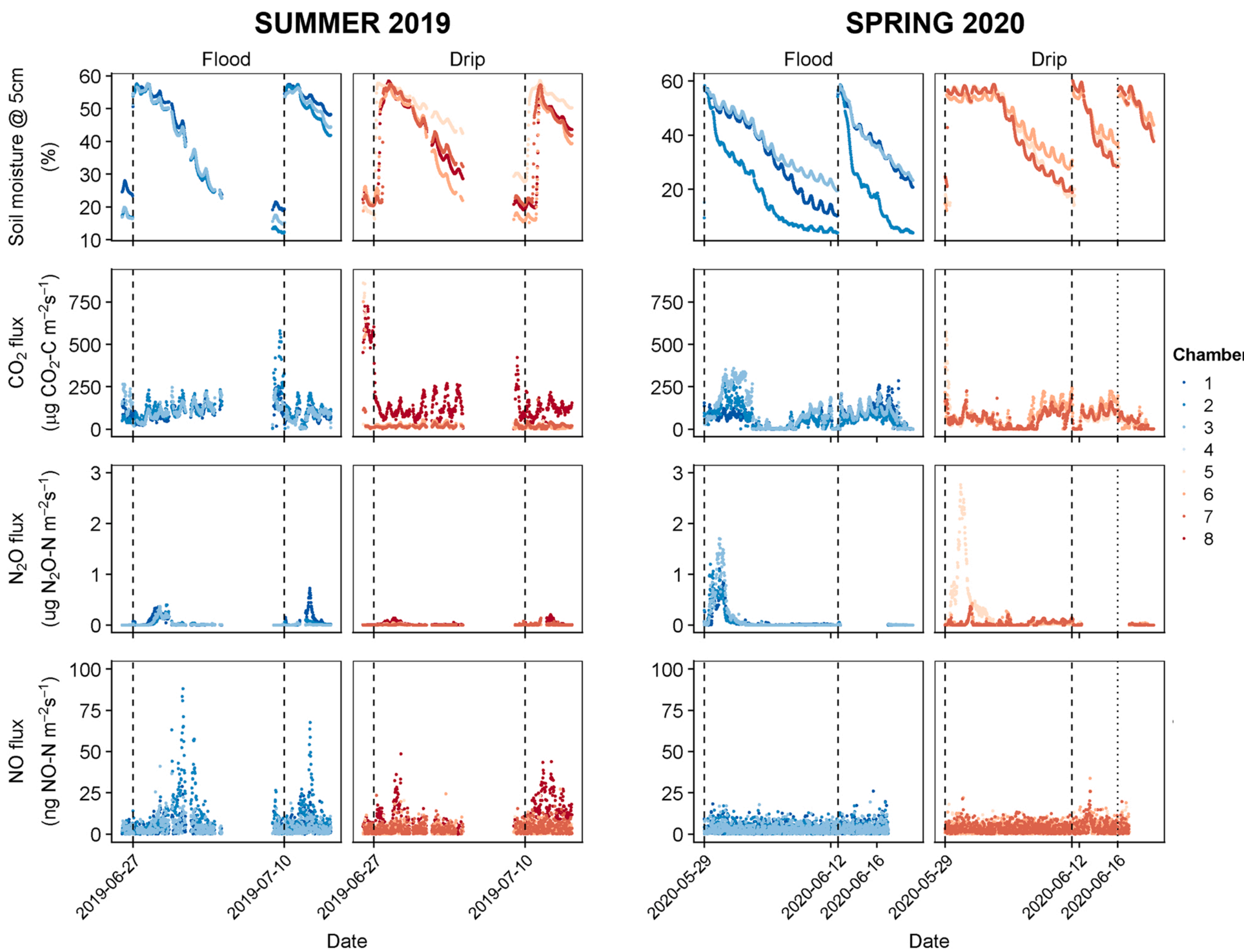

Fig. 5. Instantaneous soil moisture, carbon dioxide (CO_2), nitrous oxide (N_2O), and nitric oxide (NO) fluxes measured in alfalfa. Three to four chambers were installed in each irrigation treatment. Flood-irrigated chambers are colored blue and drip-irrigated chambers are colored red; individual chambers are delineated by color saturation. Dotted vertical lines delineate scheduled irrigation events within each campaign.

Compared to traditional surface irrigation, subsurface drip increased yield of both sudangrass and alfalfa and simultaneously reduced per-yield irrigation and per-yield soil emissions of CO_2, N_2O, and NO (Table 1). Drip irrigation in sudangrass increased crop yields by 6% and per-yield soil CO_2 emissions by 9%, while decreasing irrigation demand by 49%, N_2O emissions by 59%, and NO by 49%. In alfalfa, drip irrigation increased crop yields by 7%, while decreasing irrigation by 1%, per-yield soil CO_2 emissions by 59%, N_2O by 38%, and NO by 20%. The benefits of drip irrigation for reducing soil N emissions were particularly strong for sudangrass, a crop requiring N fertigation, and in summer harvests, when average soil temperature and irrigation needs were high. Conversely, soil CO_2 emissions were substantially lower in drip-irrigated alfalfa, suggesting reduced microbial access to C when water infiltration was restricted.

The reduction in emissions without corresponding decrease - in most cases increase - in yield suggests agronomic benefits of drip irrigation for both productivity and N use requirements, as well as important consequences for both regional air quality and greenhouse gas emissions. High-temperature regions emit NO in amounts that can increase surface O_3 concentrations (Oikawa et al., 2015; Sha et al., 2021), a contributor to respiratory illness, and the expanded use of drip irrigation may provide an opportunity to improve regional air quality. As a tool to reduce greenhouse gas emissions, the benefits of drip irrigation are well documented (Kuang et al., 2021); nevertheless, our results in sudangrass show reductions in N_2O emissions that are greater than the estimated global average of 32% (Kuang et al., 2021) and similar to California modeled estimates of 67% (Deng et al., 2018a), suggesting that applications of drip irrigation (and fertigation) in high-temperature agricultural regions may be especially useful for reducing greenhouse gas emissions. While further studies are needed to constrain annual and seasonal emission estimates and extend field level analyses to regional scales, our results suggest multiple benefits from reduced trace gas emissions associated with drip infrastructure in drylands. Additionally, our observations can lead to improvement of biogenic emission estimates in chemistry transport and Earth system models to further advance the simulation and prediction of air quality and climate change (Deng et al., 2018b; Sha et al., 2021; Wang et al., 2021).

4.1. CO_2, N_2O, and NO responses to irrigation in arid forage agriculture

Soil irrigation triggered emission pulses of trace gases lasting hours (N_2O) to days (NO and CO_2). Immediately following irrigation soil CO_2 emissions were suppressed, which has been reported previously at this site (Oikawa et al., 2014). Between 24- and 48-hours following CO_2 suppression, N_2O pulses peaked. NO pulses peaked between 50–200 h, lagging N_2O emissions and matching the post-suppression increases in CO_2 emissions. Because N_2O pulses were synchronized with CO_2 suppression and NO pulses coincided with CO_2 increases post-suppression, we suspect O_2 depletion immediately following wetting and subsequent increase as soils dry was a key mechanism driving soil metabolic processes following irrigation (Oikawa et al., 2014; Sihi et al., 2020; Wang et al., 2017) and suggest that future work investigate these mechanisms

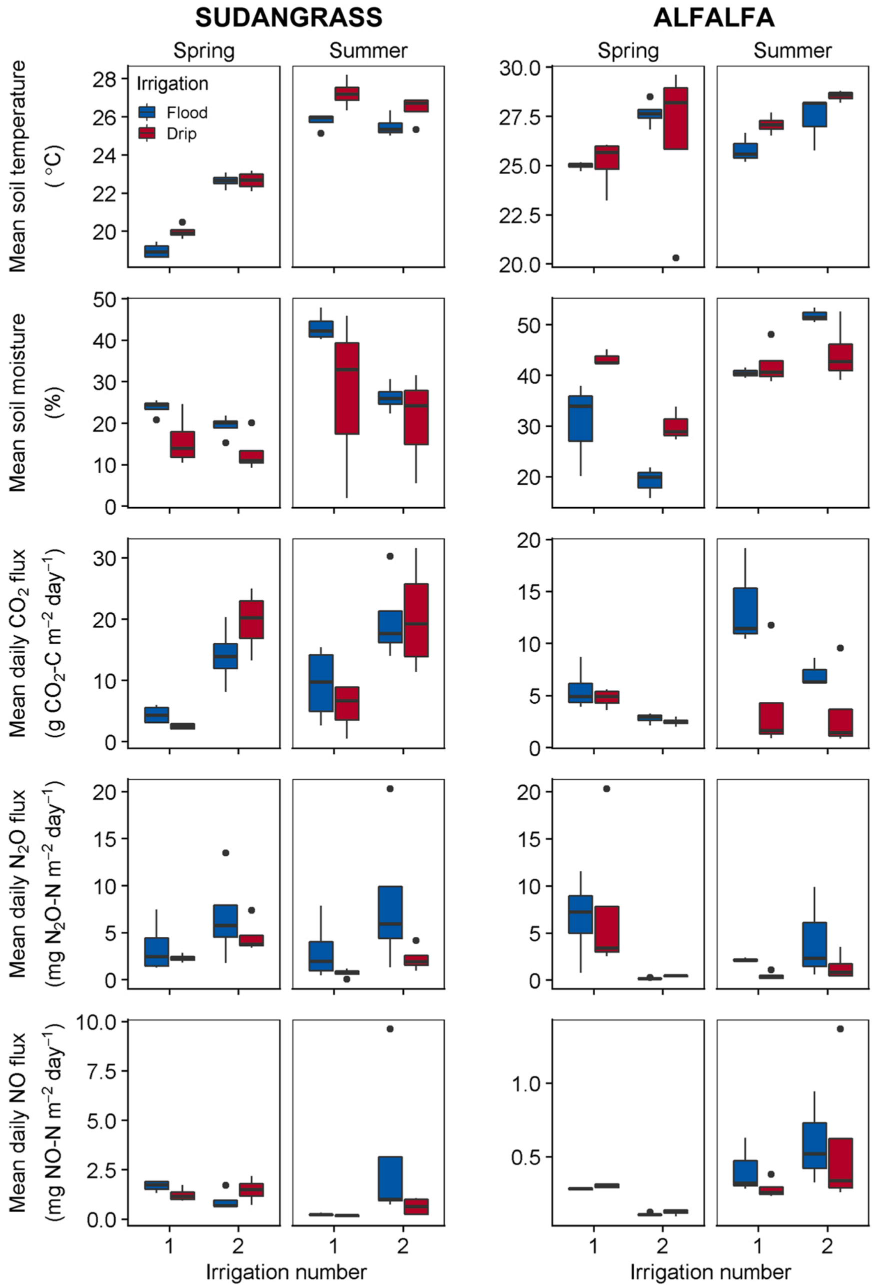

Fig. 6. Mean daily soil temperature, moisture, carbon dioxide (CO_2), nitrous oxide (N_2O), and nitric oxide (NO) fluxes following two irrigation events. Temperature and moisture were measured at 5 cm soil depth. Colors indicate flood (blue) and drip (red) irrigation treatments. Mean daily fluxes were calculated as the area-under-the-curve total flux divided by the number of days between one irrigation event and the next.

more explicitly. To our knowledge, few agricultural studies have explored fluctuations of NO at scales finer than weekly (Kennedy et al., 2013; Kuang et al., 2021; Meixner et al., 1997;) and as a result may be inaccurately estimating daily emission rates when they are dominated by pulse dynamics. Compared with non-agricultural drylands where pulses can occur within minutes to hours of rewetting (Andrews and Jenerette, 2020; Eberwein et al., 2020; Sponseller, 2007), our agricultural pulses of CO_2, N_2O, and NO were delayed and remained elevated for a longer duration. Our findings reinforce the perspective that irrigation is an important trigger of agricultural trace gas emissions (Deng et al., 2018a; Sapkota et al., 2020) and provide a first characterization of these trajectories at a fine resolution.

We observed strong variations in emissions depending on which irrigation event we measured within each measurement campaign, which we assume to be linked to plant growth status. In sudangrass, the second irrigation event consistently resulted in higher emissions of CO_2 and N_2O compared to the first, with less clear signals for NO (Fig. 6); we attribute this trend to increasing activation of plant root respiration and release of exudates that prime soil microbial communities. We did not partition roots from bulk soil in our measurements of CO_2 emissions but suspect that the contribution of roots to whole-soil respiration is likely high given the large biomass that sudangrass produces. Additionally, root exudates provide a C source that is required for soil microbial CO_2 and N_2O production, further contributing to larger soil emissions of these gases. In alfalfa, subsequent irrigations tended to reduce emissions, suggesting that without external fertilizers, growing alfalfa competes strongly for soil C and N, particularly in the drip-irrigated field, contributing to tight internal cycling of nutrients with few losses to the atmosphere. Crop-dependent, contrasting patterns of emissions over the course of a harvest show that plant physiology and life history strategies

Table 1
Upscaled soil trace gas emissions associated with crop production. Per-yield emissions were calculated by multiplying daily mean emissions by the length of each harvest and dividing the total by per-area harvested yield. Values are reported as means (standard errors) for each treatment group.

Crop	Season	Irrigation type	Mean (SE) daily soil CO_2 emission (g CO_2-C m^{-2} day^{-1})	Mean (SE) daily soil N_2O emission (mg N_2O-N m^{-2} day^{-1})	Mean (SE) daily soil NO emission (mg NO-N m^{-2} day^{-1})	Days to harvest (days)	Harvest yield (g m^{-2})	Mean (SE) per-yield soil CO_2 emission (g CO_2-C g^{-1} yield)	Mean (SE) per-yield soil N_2O emission (mg N_2O-N g^{-1} yield)	Mean (SE) per-yield soil NO emission (mg NO-N g^{-1} yield)
Sudangrass	Spring	Flood	9.24 (1.31)	5.07 (1.90)	1.31 (0.14)	69	536.888	1.19 (0.17)	0.65 (0.24)	0.17 (0.02)
		Drip	11.09 (1.28)	3.44 (0.40)	1.36 (0.24)	69	537.560	1.42 (0.16)	0.44 (0.05)	0.17 (0.03)
	Summer	Flood	14.63 (2.83)	5.73 (2.31)	1.67 (1.08)	92	549.217	2.45 (0.47)	0.96 (0.39)	0.28 (0.18)
		Drip	13.05 (1.80)	1.48 (0.41)	0.41 (0.12)	92	627.677	1.91 (0.26)	0.22 (0.06)	0.06 (0.02)
Alfalfa	Summer	Flood	4.22 (0.60)	3.44 (1.11)	0.19 (0.00)	37	331.772	0.36 (0.05)	0.29 (0.09)	0.02 (0.00)
		Drip	3.63 (0.26)	3.94 (2.13)	0.21 (0.01)	37	289.180	0.35 (0.03)	0.38 (0.21)	0.02 (0.00)
	Spring	Flood	10.37 (1.77)	3.21 (1.49)	0.50 (1.14)	28	226.412	1.69 (0.29)	0.53 (0.24)	0.08 (0.02)
		Drip	3.66 (2.34)	0.92 (0.47)	0.43 (0.15)	28	271.246	0.50 (0.32)	0.13 (0.06)	0.06 (0.02)

can constrain the effectiveness of irrigation.

4.2. Effects of drip irrigation on pulses and per-yield emissions of CO_2, N_2O, and NO

In almost all of our field campaigns, drip irrigation reduced per-yield and mean daily emissions of CO_2, N_2O, and NO compared to flood irrigation, a result that contrasts to a recent review showing increases or inconsistent changes in greenhouse gas emissions under drip irrigation (Sapkota et al., 2020). Drip-irrigated soils tended to be hotter than flood-irrigated soils (Fig. 6), particularly in summer, which would suggest stronger emission responses to irrigation; the lower emissions we observed were, therefore, primarily driven by crop-dependent nutrient and water applications, as have been predicted in process models (Deng et al., 2018b). Irrigation and fertilization are subject to management decisions and, as in the case of our study, often co-vary, indicating decreases in emissions can be most influenced by integrating multiple field management strategies directly (Kennedy et al., 2013; Sanz-Cobena et al., 2017).

Our findings are consistent with the hypothesis that targeted, slow-release drip irrigation reduced soil drying-rewetting cycles and led to increased retention of soil N that was inaccessible to microbes (Leitner et al., 2017). Conversely, flood irrigation flushed soils with N over a shorter time period and caused more N to leak through trace gaseous pathways (Almaraz et al., 2018) and presumably hydrologic pathways as well. Although sudangrass flood and drip fields experienced different fertigation regimes in our study, the increase in yield we observed in drip fields despite lower fertilizer inputs suggests this management strategy is more effective than few, large fertigations in flood irrigation systems while also reducing per-yield emissions. Measurements of drip irrigation systems in milder climates and for other crops further support this hypothesis for CO_2 and/or N_2O emissions (Kallenbach et al., 2010; Kuang et al., 2021; Wei et al., 2021) and suggests greater effects than previously observed for NO emissions (Sánchez-Martín et al., 2008; Sánchez-Martín, 2010). By altering the location, availability, and timing of water and fertilizer additions, drip irrigation systems altered soil moisture and nutrient availability coincident with reduced trace gas emissions.

4.3. Crop type contributions to irrigation effectiveness

Differences in plant physiology and corresponding management strategies between sudangrass and alfalfa resulted in a different effectiveness of drip compared to flood irrigation. Although sudangrass and alfalfa have similar water requirements (Grismer, 2001), furrow fertigation in sudangrass compared to whole-field flooding in alfalfa likely result in differences in nutrient and water percolation that make it difficult to compare these crops directly. In addition to differences in yield and WUE between the two crops, alfalfa and sudangrass were associated with differing trace gas emissions and their sensitivity to irrigation management. In alfalfa, drip irrigation primarily reduced per-yield emissions of soil CO_2 by suppressing CO_2 production for a longer period than under flood irrigation; we also observed smaller N_2O pulses and greater accumulation of extractable N in alfalfa drip soils. These two lines of evidence suggest that drip irrigation reduced microbial access to organic matter and constrained production of trace gases requiring C substrates (Homyak et al., 2018; Liang et al., 2015). Conversely, drip irrigation in sudangrass had more limited effect on CO_2 emissions, partially supporting a recent review of greenhouse gas responses to irrigation (Sapkota et al., 2020) but led to a greater reduction of N_2O and NO emissions, consistent with previous work in vegetable crops (Kallenbach et al., 2010). Emissions of both N gases in sudangrass decreased by 60–70% with drip management, suggesting that sustained water and N release into a readily-accessible location in the rhizosphere had a disproportionately large effect on emissions given only a 25% reduction in fertilizer N inputs. We suspect N applied in flood fertigation was immediately lost rather than incorporated into plant biomass, resulting in lower hay yields and higher N emissions compared to drip-irrigated counterparts. We note that our estimates of N losses from flooded sudangrass fields may be conservative since we did not measure emissions from furrows, where water and fertilizers were directly applied. Future studies should consider topographical and percolation effects on irrigation-emissions relationships. Based on our findings, drip-line implementation lowered trace gas emissions from alfalfa and sudangrass compared to surface irrigation but predominantly through CO_2 pathways in alfalfa and N emissions pathways in sudangrass.

4.4. Seasonal contributions to irrigation effectiveness

Emissions of CO_2, N_2O, and NO were larger in soils measured in summer compared to spring, supporting our hypothesis that higher soil temperatures and larger irrigation events stimulate stronger pulse responses and per-yield emissions. The combination of both temperature and moisture explain most clearly the seasonal increases in CO_2 pulses from flood-irrigated soils, as microbial enzyme kinetics and substrate availability would both be expected to increase in these conditions (Bowling et al., 2011; Liang et al., 2016). These findings are also consistent with models that include temperature dependence for both CO_2 and N trace gas emissions (Davidson et al., 2012; Oikawa et al., 2016; Wang et al., 2021). Seasonality also reflected different levels of root development, as both crops were harvested multiple times throughout the year, and disentangling the seasonal effects of weather from harvest history remains a challenge (Garland et al., 2014). Summer likely had the most mature root biomass for sudangrass compared to spring for alfalfa, which could affect nutrient and water acquisition differently from climatic regimes. We suggest that future work examining interactions among meteorology and harvest history is an important research direction to better understand the effects of seasonality on agricultural trace gas emissions.

5. Conclusion

Agricultural soils are a large source of trace gas emissions, including greenhouse gases (CO_2 and N_2O) and precursors (NO) to harmful air pollutants; the majority of emissions from these systems occur following scheduled irrigation events which also put pressure on limited water resources in dryland regions (Putnam and Kallenbach, 1997). We show that surface flood irrigation produces large pulses of CO_2, N_2O, and NO in two widely-planted forage crops. However, implementation of water-conservative subsurface drip irrigation can reduce trace gas emission pulses of these gases while simultaneously reducing irrigation and improving yield. In crop-specific contexts, drip irrigation in unfertilized alfalfa largely reduced per-yield CO_2 emissions while in fertilized sudangrass it reduced N_2O and NO emissions by over 45% (Table 1). Drip irrigation also proved more advantageous with seasonal increases in temperature and moisture, avoiding the increases in pulses that were experienced in flood-irrigated fields. Although implementation of drip infrastructure can be costly (Sanz-Cobena et al., 2017), costs may be offset through carbon credit programs (e.g. California Cap-and-Trade program) that pay for N_2O emission reductions (Niles et al., 2019; Wolf et al., 2020). To meet climate change mitigation scenarios (IPCC, 2019) and demand for forage crops (Putnam and Kallenbach, 1997) and to improve public health (Hall et al., 1996), agricultural management strategies must be improved. For high-temperature regions like the Imperial Valley, we find subsurface drip irrigation to be a viable management strategy to increase crop yields, reduce irrigation, and constrain soil emissions of trace and greenhouse gases, providing a win-win-win alternative to traditional surface irrigation.

Declaration of Competing Interest

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

Data Availability

All raw and processed datasets generated during this study are publicly available via DRYAD Repository (https://doi.org/10.6086/D1C10T).

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agee.2022.107944.

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