Title
Orchard Floor Management: Improved Practices for Nitrogen Retention

Author
Nichols, Patrick Keith

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Orchard Floor Management: Improved Practices for Nitrogen Retention

By

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DISSERTATION

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Approved:

Kerri Steenwerth, Chair

Patrick H. Brown

Majdi Abou Najm

Committee in Charge

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Abstract

The sustainability of agricultural practices is of paramount importance in mitigating climate change. Chapter 1 of this body of work investigates the impact of alternative fertilization practices on the yield-scaled global warming potential (YS-GWP) in almond orchards. Almond production is a contributor to greenhouse gas emissions, primarily due to nitrogen-based fertilizers. By exploring alternative fertilization methods, this research aims to identify strategies that reduce the environmental footprint of almond cultivation while maintaining or enhancing yield. Field experiments were conducted in an almond orchard using three alternative fertigation practices: Advance Grower Practice (AGP), Pump and Fertilize (P&F), and High Frequency Low Concentration (HFLC). AGP followed the current practice producers generally use to meet annual N demand for almond tree growth; P&F is a reduction in applied N rate in response to measured N concentrations in the groundwater so that the added N and groundwater N reach the same total N applied; HFLC is a practice of applying smaller N rates in an individual event, with a greater number of fertigation events to reach similar total N load applied annually as other treatments. The results revealed that both P&F and HFLC reduced the YS-GWP compared to the AGP. The HFLC fertigation demonstrated 52% to 78% decrease in GWP per unit of almond yield compared to AGP, while P&F showed 48% to 58% decrease over AGP. These reductions were attributed to the improved nitrogen use efficiency and reduced nitrous oxide emissions associated with the alternative practices. The findings of this chapter demonstrate that adopting alternative fertilization practices can effectively mitigate the environmental footprint of almond orchards while maintaining or even improving crop yields. These practices offer viable options for almond growers to reduce greenhouse gas emissions, enhance sustainability, and contribute to climate change mitigation efforts. Future research should focus on long-term monitoring of

these practices and their economic viability to support their widespread adoption in almond production systems and other similar agricultural systems.

Nitrogen management in agricultural systems plays a crucial role in optimizing crop growth and yield while minimizing environmental impact. The second chapter of this body of work aimed to investigate the dynamics of applied nitrogen during high frequency-low concentration fertigation in a California almond orchard. The experiment was conducted over three growing seasons in a commercial almond orchard located in California's Central Valley. Fertigation was applied as high frequency-low concentration fertigation (HFLC). I analyzed HFLC at an orchard scale, and how the variability of the soil and irrigation distribution might translate into flux estimations. Nitrogen was applied through either drip irrigation or fanjet micro sprinklers across four orchard blocks. I analyzed HFLC at an orchard scale, and how the variability of the soil and irrigation distribution might translate into flux estimations. Several parameters were monitored throughout the study, including GHG emissions, soil nitrogen content, various soil physicochemical factors and almond yield. This work provided some insight into the dynamics of N loss through soil N_2O production during the application of HFLC fertigation on an almond orchard. While HFLC fertigation strategy has demonstrated a reduced potential for nitrogen losses, minimizing the environmental impact and promoting sustainable almond production, the influence of irrigation type and soil physicochemical factors needs further elucidation. No significant correlations were revealed in the data collected for this chapter. This chapter presents a comprehensive analysis of the dynamics of applied nitrogen during high frequency-low concentration fertigation in a California almond orchard. The findings highlight the need for further examination of the potential for this innovative approach in improving nitrogen use efficiency and reducing nitrogen losses to the environment. These insights can contribute to the development of sustainable nitrogen management practices in almond orchards and other similar agricultural systems, thereby ensuring the long-term viability of crop production while safeguarding environmental resources.

Compost's use as an agricultural amendment offers an opportunity to reduce organic waste, as mandated in the State of California (USA) (SB 1383). Organic soil amendments, such as compost, can improve soil physical characteristics, nutrient cycling and soil carbon through the increase in soil organic matter. Fertilizer application through micro irrigation systems (i.e. fertigation) is increasingly common in almonds in California's Central Valley, as it is an effective method to manage water availability and nutrient loss. In the third chapter of this body of work I examined the effect of compost application (7-year duration) on soil nitrous oxide emissions, inorganic N pools, soil temperature and water content, soil bulk density, and total C and N content. The almond orchard (Nonpareil cultivars interplanted with Aldrich and Carmel cultivars, all grafted on 'Nemaguard' peach rootstock [Prunus *persica* (L.) Bratsch]) was on an Oakdale sandy loam soil type. It was fertigated 14 times with urea ammonium nitrate or calcium ammonium nitrate, using high frequency and low concentration (HF-LC) applications, for a total of 195 kg N ha^{-1}. Soil without added compost ('no compost') tended to have higher fluxes (up to 2.75-fold) than soil with compost ('compost'). Emissions from 'no-compost' ranged from 0.29 to 5.5 g N_2O-N ha^{-1} day^{-1} while 'compost' ranged from 0.34 to 3.7 g N_2O-N ha^{-1} day^{-1}. Additionally, I observed a substantial reduction in annual cumulative N_2O emissions from 'compost', 11.5 g N-N_20 ha^{-1} compared to 20.1 g N-N_20 ha^{-1} in 'no compost'. Soil pH, EC, total C and N tended to be greater in 'compost', and bulk density tended to lower in 'compost' than 'no-compost'. No relationships between N_2O emissions and soil temperature, volumetric water content, water-filled pore space, and inorganic N pools were observed in either treatment. The findings in this chapter indicate that long-term applications of compost in perennial crops, in combination with a HF-LC nutrient management program, could reduce losses of N as N_2O to the atmosphere.

Dissertation Chapter 1

Title: Alternative fertilization practices lead to improvements in yield-scaled global warming potential in almond orchards

Authors: Patrick K. Nichols[1 & 2]*, Sharon Dabach[1], Rebekah Davis[1], Patrick Brown[3], David Smart[1†], Kerri Steenwerth[4]*

[1] Department of Viticulture and Enology, University of California Davis, One Shields Avenue, Davis, CA 95616, United States

[2] Department of Land, Air & Water Resources, University of California Davis, One Shields Avenue, Davis, CA 95616, United States

[3] Department of Plant Sciences, University of California Davis, One Shields Avenue, Davis, CA 95616, United States

[4] USDA-ARS, Crops Pathology and Genetics Research Unit, Department of Land, Air & Water Resources, University of California, Davis, CA, United Sates

*Corresponding author

[†]Post-humous author

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Introduction

Demand for agricultural products has been increasing concomitantly with global population growth, driving the need for greater yields from arable land. Global population growth is estimated to plateau near 9 billion people by 2050 (Godfray et al., 2010; World Bank, 2008; FAOSTAT, 2015). The need to feed this population by increasing agricultural productivity upon finite arable land area is driving increased use of fertilizer nitrogen (N) (Garnett, 2014). The resulting global demand for fertilizer N has led to an 8% annual increase in its application from 2010 to 2017, exceeding 109 Tg throughout the world's crop producing regions (FAO, 2018). Widespread and potentially excessive application of synthetic N combined with other practices such as tillage, on-demand irrigation, pesticide and agrochemical applications has driven soil degradation, and water and air pollution (Lal, 2008). The use of synthetic N fertilizer, while increasing crop yields, leads to increases in greenhouse gas (GHG) emissions from soil (Cole, 1996; Prather, 1995; Smith et al., 2007). No crop production system has yet to achieve 100% N use efficiency, including California almond orchards.

Nitrogen losses from orchards occur in various gaseous forms (e.g., nitrous oxide [N_2O], oxides of nitrogen [NOx], dinitrogen [N_2]) and as dissolved solutes (e.g., nitrate [NO_3^-], ammonium [NH_4^+]) in leachate to groundwater or surface runoff. Offsite transport of reactive nitrogen (NH_4^+, NO_3^-, NH_3, NOx and N_2O) and other greenhouse gasses (GHGs) from agriculture are facing increased regulatory scrutiny (e.g. Central Valley Irrigated Lands Regulatory Program, Central Valley Salinity Alternatives for Long-Term Sustainability plan, California Air Resources Board – Soil Emissions from California Lands program) due to their impacts on climate, and air and drinking water quality (Galloway et al., 2002).

Nitrous oxide production from soil occurs as a byproduct from nitrification and denitrification (Verhoeven, 2017). It is well known that soil microorganisms produce nitrous oxide through nitrification, denitrification, nitrifier-denitrification, hydroxylamine decomposition and chemodenitrification (Zhu-Barker & Steenwerth, 2018). These microbiological processes that produce N_2O are controlled by soil carbon (C), N and oxygen (O_2) availability and physical factors that affect gaseous and solute diffusion and transport through the soil (Williams et al., 1992;Stanford & Epstein, 1974; Zhu-Barker & Steenwerth, 2018). As such, they are sensitive to management practices like N fertilization and irrigation.

Our work focuses on determining yield-scaled greenhouse gas (GHG) emissions from almond orchards to identify best irrigation methods to deliver N fertilizer (i.e. fertigation) and reduce associated GHG emissions. Scaling GHG emissions with respect to the corresponding crop yields can relativize the cost-benefit of fertilizer N use. This scaling approach is known as yield-scaled global warming potential (YS-GWP) and has been used in a number of California studies noted here (Mosier et al., 2006; van Groenigen et al., 2012; Linquist et al., 2012; Schellenberg et al., 2012; Feng et al., 2013; Pittelkow et al., 2013; Bayer et al., 2014; Tarlera et al., 2016). YS-GWP in almond orchards fertigated through micro-sprinklers varied by type of inorganic N; calcium ammonium nitrate fertilizer tended toward lower YS-GWP than urea ammonium nitrate (Kern County, CA; Schellenberg et al., 2012). Placement and type of fertilizer can affect YS-GWP; knife-injected anhydrous ammonia resulted in higher yield scaled nitrous oxide (YS-N_2O) production relative to other N applications in wheat fields (Dixon, CA; Zhu-Barker et al., 2015). In rice paddies, N_2O emission tended to increase as the applied rates of N fertilizers increased, while YS-GWP was minimized at optimum yields with respect to N fertilizer application (Arbuckle, CA; Pittelkow et al. 2013).

Almonds are a logical crop upon which to focus to reduce global and statewide GHG emissions from agriculture. Almonds grown in California account for approximately 80% of global production and 100% of domestic production (USDA, 2018). Their global productivity (tonnes per year) grew nearly 21% from 2014 to 2018 (FAOSTAT, 2018), and in 2019, California supported over 619,000 planted hectares with a production value worth approximately $5.6 billion (CDFA, 2020). As such, they were the highest valued fruit or nut crop in the state. A mature almond orchard in California annually receives about 224 kg N ha^{-1} and requires between 8,000 and 13,000 m^3 ha^{-1} of water depending on irrigation type (Kendall et al., 2015). Irrigation with micro-sprinkler and drip systems is increasingly common, and most of the N fertilizer is applied through these systems, a practice known as fertigation (Lopus et al., 2010). In these almond orchards, soil water content and N availability are functions of fertigation practices that drive nitrification and denitrification processes, leading to nitrous oxide (N_2O) production (Smart et al., 2011). Nitrous oxide composes nearly half of the GHGs attributed to California's agricultural emissions, which is approximately 8% of the state's total GHG emissions (CARB, 2017).

Little is known about the potential for constraining YS-GWP in almonds by controlling N application rates and timing through fertigation. Here, we examine the response of YS-GWP in an almond orchard under a combination of different fertilizer-irrigation practices controlling frequency of N application. We hypothesize that applying smaller N amounts more frequently than the standard practice will result in a lower YS-GWP. A similar quantity of N will be applied to meet the annual tree demand for N, but smaller quantities more frequently will reduce the available N sources for microbial processes at a given time. By providing a similar quantity of N as standard practices by the end of the growing season, the almond yield will not be affected by lower N rates applied more frequently, and the annual cumulative emissions of N_2O will be lower than the standard practices.

Materials and Methods

Research site

The study was conducted in a commercial almond orchard (16 ha) during the 2015 and 2016 growing seasons in the San Joaquin Valley (Madera, California; 36° 49’ 15.85” N 120° 12’1.20 W, elevation 60 m). The mature trees (ca.16 years, 73 trees per row) were spaced 5.5 m tree to tree within row and approximately 14.6 m between alternating rows of Nonpareil and Carmel cultivars. The Cajon series soil (*Mixed, thermic Typic Torripsamments*) is characterized by loose fine sand with low organic carbon content and low water holding capacity (Soil Survey Staff, 2021). The study site is located on a distal alluvial fan (trough cross beds) of the San Joaquin River consisting of coarse silt over sand joined with a sandy loam that formed from predominantly granite parent material (Baram et al., 2016, California Soils Resource Lab, 2015). The site has a semi-arid climate with warm dry summers and an average annual high temperature of 24 °C, average annual low of 9 °C, and an average precipitation of 304.8 mm $year^{-1}$ predominantly occurring during winter (Dec. - Feb.) (CIMIS, 2016). The site received 228 mm and 347 mm of precipitation during 2015 and 2016, respectively. Rooting depth of the almond orchard was approximately three meters, with most of the roots (>90%) within the first meter (Baram et al., 2016).

Irrigation systems and controlled fertigation of N load

Three treatments were applied in a randomized complete block design, with four replicates of each treatment: Advance Grower Practice (AGP), Pump and Fertilize (P&F), and High Frequency Low Concentration (HFLC). AGP followed the current practice producers generally use to meet annual N demand for almond tree growth; P&F is a reduction in applied N rate in response to measured N concentrations in the groundwater so that the added N and groundwater N reach the same total N applied; HFLC is a practice of applying smaller N rates in an individual event, with a greater number of fertigation events to reach similar total N load applied annually as other treatments (Table 1.1). Within each treatment, each replicate consists of an array of collars and chambers (described below), and four arrays were installed (n=4 arrays per treatment).

Fertilizer for each respective treatment was applied through the irrigation system (fertigation) with locally pumped groundwater, using Urea Ammonium Nitrate solution (UAN32). UAN32 is a soluble fertilizer that is 32% nitrogen (N), composed of 50% urea-N, 25% NH_4^+-N, and 25% NO_3^- -N; (Yara North America Inc., Tampa, FL). Soluble UAN was injected into the irrigation system, and fertigation occurred via fanjet micro-sprinklers (one micro-sprinkler tree^{-1}, with a 3m wetting radius, and emitting 0.05 m^3 per hour).

All three fertigation treatments provided a similar annual total N targeted to meet the demands for high yielding commercial almond production based on above and below ground growth (Table 1.1). AGP represented the updated standard growing practice with respect to timing and quantity of fertilizer application for the local industry at the time. P&F reduced the amount of applied fertilizer N by accounting for groundwater N concentrations. The N in the groundwater contained approximately 30% of the required N application. Groundwater NO_3^- -N concentrations measured 35 mg L $^{-1}$ and 25 mg L^{-1} in 2014 and 2015, respectively. The decrease in 2015 is attributed to the addition of a deep pumping well (Baram et al., 2016). AGP and P&F treatments each had four applications in 2015 and six in 2016. In HFLC, fertilizer N was applied during 13 and 18 fertigation events in 2015 and 2016 growing seasons, respectively (ca.12 kg N ha^{-1} per event). At the grower's request, fertigation applications increased in 2016 to six AGP and P&F applications and 18 HFLC applications, increasing total N load approximately 10-30% between the seasons.

Gas Sampling and Soil Data

Gas flux measurements were taken every 1-2 weeks throughout the growing season from March-August and post-harvest (Sept.-Dec.), depending on the grower's irrigation and nutrient management schedule. During the winter (Jan.-Feb.), no data were collected due to an absence of fertigation during tree dormancy. Gas flux rates were measured using the closed chamber method (Livingston and Hutchinson, 1995). Each treatment replicate had one sampling array, consisting of five collars per sampling array (n=4 arrays per treatment, as above). Each collar was 20 cm in diameter, 8 cm tall and installed 5 cm into the soil, leaving 3 cm above the soil surface. The five collars were placed in a transect perpendicular to the row, at distances of 0cm, 50cm, 100cm, 150cm, and 200cm from the micro-sprinkler at the head of the berm to near the center of the alleyway between the tree rows (Figure 1.1). Gas samples were taken within 2-3 days following fertigation or irrigation events.

On collection days, static chambers (each 3.5 liters volume) constructed according to Parkin and Venterea (2010) were placed on preinstalled collars (for a total sampled volume of 4.5 liters). Ambient gas samples were collected at time 0. The chamber headspace then was sampled at 10 and 20 minutes. Gas samples were injected into evacuated glass vial exetainers (20

cm^3 into 12 cm^3; Exetainer®, Labco Limited, Buckinghamshire UK). Samples were analyzed using a gas chromatograph GC-2014 Shimadzu, furnished with a ^{63}Ni electron capture detector for measurement of GHGs. Simultaneous to gas collection, soil conditions were characterized. Soil volumetric water content (θ_v) and temperature were collected from the 0-10 cm depth using a ProCheck Decagon Device with a 5TE sensor (Decagon Devices, Inc.). Soil samples (0-30 cm × 2 cm diam) were collected adjacent to each collar from one replicate array, alternating replicates during each event. Each soil sample was homogenized, and inorganic N was extracted from soil (ca. 5 g) in 50 ml of 2M KCl solution and analyzed for nitrate and ammonium concentrations colorimetrically (Alef & Nannipieri, 1995; Kempers & Kok, 1989; Miranda et al., 2001).

Harvest

The mature almonds were harvested following standard industry practices on August 15th 2015 and August 22nd 2016 by shaking trees with an almond tree shaker. Fruit was dried on the orchard floor between 9 and 11 days, swept into windrows and collected by harvester machines when fruit reached approximately 6% water content by weight. Three subsamples of almonds (hulls and kernels) within each treatment row were taken for mass fraction analysis to determine kernel yield (Muhammad et al., 2015). Kernel yield for each treatment (n=3 per year) was then used for analysis of treatment effects.

Flux and Yield-scaled GWP

Linear regressions of chamber concentration were used to calculate gas flux rates (q) [g cm^{-2} h^{-1}] in addition to the ideal gas law according to:

[1]	$$q = \frac{dC_{gas}}{dt} * \frac{V_{chamber}}{A_{chamber}} * \frac{P}{RT} * M_w$$

where C_{gas} is the measured gas concentration [μL L^{-1}], t is time [hour], $V_{chamber}$ [cm^3] and $A_{chamber}$ [cm^2] are the chamber volume and surface area respectively, P is the ambient pressure [0.988 atm], R is the gas law constant [0.08206 l atm mol^{-1} K^{-1}], T is the temperature [K], and M_w is the molecular weight of the gas [g mol^{-1}]. Daily flux values were estimated assuming the measured fluxes were the daily average (Schellenberg et al., 2012).

Nitrous oxide emission measurements around the micro-sprinkler emitters were upscaled to the orchard level using a unit tree area (Baram et al., 2018). The wetted area around a tree can be represented by a circle with a 225 cm wetting radius (distance of emitter distribution). Every chamber measurement would then represent a 50 cm radius wetted disk. The 0 cm measurement represented a 25 cm radius wetted disk. This approach assumes each measurement position was representative of the gas flux of the wetted area of the circle the emitter deposited at that distance around the emitter (Schellenberg et al., 2012). Calculated emissions were then summed and multiplied by the given wetted disk areas to give total N_2O emission per tree:

[2]	$$Q_{Tree} = \sum_{i=0}^{r_{max}} \pi q_i (r_{i+x}^2 - r_i^2)$$

where Q_{Tree} is total emission per tree [ng N_2O-N h^{-1}], q_i is the emission rate measured at the i^{th} collar [ng N_2O-N cm^{-2} h^{-1}], i is the distance from the emitter (cm), *x* is the width of the wetted disk (cm), following Baram et al.(2018).

Cumulative N_2O and CH_4 emissions were used to determine GWP by converting the emissions to carbon dioxide equivalents within a 100-year horizon according to the IPCC method of multiplying N_2O emissions by a radiative forcing potential CO_2 equivalent of 298 and CH_4 by 84 (IPCC, 2001). Soil CO_2 fluxes were not incorporated as it generally is considered offset by the high primary productivity and associated CO_2 fixation by cropping systems (Linquist, 2012). Yield-scaled global warming potential (CO_2eq Mg^{-1}) for each treatment per year was calculated by dividing the cumulative GHG emissions (CO_2eq ha^{-1} yr^{-1}) for each growing season by the total almond kernel yield (Mg ha^{-1} yr^{-1}) for the growing season as described by Schellenberg et al. (2012).

Statistical analysis

Measurements from 2015 and 2016 were analyzed separately from each other because the grower changed the number of fertigation events and total amount of applied N each year. Measured N_2O flux was analyzed as daily emissions per tree, using a mixed model for repeated measures, upon which an analysis of variance (ANOVA) was conducted to determine effects of treatment ('AGP', 'P&F', 'HFLC'), date and treatment × date ($p<0.05$) (lmer in R Project, http://r-project.org). Soil volumetric water content (Θ_v) and temperature were analyzed using a mixed model for repeated measures and ANOVA to determine effects of treatment, date and treatment × date ($p<0.05$). Treatment and date were fixed effects, and replicate array was a random effect. Variables were tested for normality and homogeneity of variances (Shapiro-Wilk's method). The variable N_2O was transformed by natural log to meet these criteria, but untransformed emissions data were plotted. Post-hoc pairwise comparisons were conducted using Kenward-Roger method and Tukey adjustment based on *a priori* hypotheses that N_2O fluxes, Θ_v, and soil temperature would vary among fertigation treatments. ANOVA was conducted to test for effects of year, treatment and year × treatment on almond yield and YS-GWP ($p<0.05$) (lme4 in R Project, http://r-project.org) (see Table 1.2). All statistical analyses were conducted in R version 4.2.1 (R Core Team, 2022), using lme4 for model analysis (Bates et al., 2014), emmeans for post-hoc analysis (Lenth, 2020) and ggplot2 for figures (Villanueva & Chen, 2019).

Results

Yields remained constant between years with respect to the three different fertigation treatments ($p = 0.3340$) (Table 1.2, Figure 1.2). There was no effect of year ($p = 0.4728$), treatment ($p = 0.3340$), or year × treatment ($p = 0.9411$) on almond yields.

Soil volumetric water content (Θ_v) did not vary between fertigation treatments by sample date during 2015 or 2016 (Table 1.2, $p>0.05$). In all three fertigation treatments, Θ_v differed by sampling date in each year (Table 1.2, $p<0.001$). The interaction of treatment × sampling date was not significant for either year (Table 1.2, $p>0.05$). In 2015, Θ_v ranged from approximately 11% to 21% across the treatments, and in 2016 it was between 3% and 17% across the treatments. Θ_v follows similar patterns in each treatment over time, and this can be observed during both years (Figure 1.3).

Soil temperature during sampling events tended to follow a similar pattern in each treatment over time but did not differ by treatment for either year (Table 1.2, $p>0.05$). The sampling date had a significant influence on the soil temperature ($p<0.001$) for both 2015 and 2016. The interaction of treatment × sampling date was not significant for either year (Table 1.2,

$p>0.05$). From December to July, the soil temperature ranged from approximately 13 °C to 30 °C in 2015, and from 16 °C to 32 °C in 2016 (Figure 1.4).

In 2015, soil nitrate-nitrogen (NO_3^- -N) concentration ranged from 0.196 mg kg-soil^{-1} to 26.041 mg kg-soil^{-1}, while soil ammonium-nitrogen (NH_4^+ -N) concentration ranged from 0.428 mg kg-soil^{-1} to 37.846 mg kg-soil^{-1} (Figure 1.5). The sampling date had a significant influence on NO_3^- -N concentration ($p < 0.001$), but NO_3^- -N did not differ by treatment, nor was the interaction of treatment × sampling date significant. The NH_4^+ -N concentration was not significantly influenced by treatment, sampling date, or the interaction of treatment × sampling date in 2015. The NO_3^- -N and NH_4^+ -N concentration peaked twice in both AGP and P&F treatments, with each peak following a fertigation event (in April and in May, respectively). Those fertigation events were the second and third applications of fertilizer in those treatments. In HFLC, a single peak in NO_3^- -N and NH_4^+ -N concentration was recorded following the third fertigation event (in April).

Variation by sampling date in N_2O emissions closely followed fertigation management practices, with peak emissions generally occurring within three days of fertigation events (Figures 1.6). In 2015, mean N_2O fluxes from all treatments ranged from 0.789 g N_2O-N ha^{-1} day^{-1} to 212 g N_2O-N ha^{-1} day^{-1}. In AGP, mean N_2O fluxes ranged from 1.93 to 212 g N_2O-N ha^{-1} day^{-1}. The P&F N_2O fluxes ranged from 0.789 to 86.0 g N_2O-N ha^{-1} day^{-1}, while those from HFLC ranged from 1.78 to 56.3 g N_2O-N ha^{-1} day^{-1} (Figure 1.6). In 2016, N_2O fluxes from all treatments ranged from 0.0193 to 64.0 g N_2O-N ha^{-1} day^{-1}. Fluxes from AGP ranged from 0.0245 to 64.0 g N_2O-N ha^{-1} day^{-1}. Those from P&F ranged from 0.0193 to 24.8 g N_2O-N ha^{-1} day^{-1}, and from HFLC, they ranged from 0.0197 to 17.2 g N_2O-N ha^{-1} day^{-1} (Figure 1.6). In both 2015 and

2016, daily N_2O emissions tended to be lower in HFLC compared to AGP and P&F, but with similar temporal patterns throughout the year.

At the onset of the 2015 and 2016 fertigation programs in March, N_2O emissions tended to be similar among the three treatments. As the trees became more active physiologically in April and May, N_2O fluxes tended to diverge among treatments in both years. During this divergent period, peak fluxes were recorded in all treatments during both 2015 and 2016. In November, fluxes again tended to be similar across the three treatments (Figures 1.6).

The effect of treatment and interaction between treatment × sampling date on daily mean N_2O emissions was not significant in 2015; only sampling date had a significant ($p < 0.001$) effect that year (Table 1.2). However, the effect of sampling date, treatment, and the interaction between treatment × sampling date were all significant in 2016 (Table 1.2, $p < 0.05$). Significant differences between AGP and HFLC can be observed during sampling dates in March ($p < 0.001$), April ($p < 0.01$), and May ($p < 0.05$) in 2016. Daily mean N_2O emissions did not differ significantly between AGP and P&F or between P&F and HFLC on any of the sampling dates (Figure 1.6).

Cumulative measured totals of N_2O emissions followed the same order both years, with AGP > P&F > HFLC (Supplemental Table 1.1). Cumulative N_2O emissions differed by treatment in both 2015 and 2016 ($p < 0.05$). In 2015, cumulative N_2O emissions in AGP tended to be approximately 1.5-fold greater than HFLC, and in 2016 the cumulative N_2O emissions in AGP tended to be about 1.78-fold greater than HFLC. Decreases in cumulative N_2O emissions from 2015 to 2106 ranged from 558 g ha^{-1} in AGP to 344 g ha^{-1} in P&F, while HFLC recorded a

379 g ha^{-1} decrease in cumulative N_2O emissions between the two years (Supplemental Table 1.1, Supplemental Figures 1.1 and 1.2).

Cumulative totals of CH_4 emissions from all three treatments ranged from 127 g ha^{-1} to 160 g ha^{-1} in 2015 and from 74 g ha^{-1} to 82 g ha^{-1} in 2016 (Supplemental Figures 1.1 and 1.2). Treatment did not significantly impact cumulative CH_4 emissions either year. The highest cumulative CH_4 was recorded in AGP followed by HFLC and P&F in both years. In 2015, CH_4 emissions (160 g ha^{-1}) from AGP tended to exceed HFLC emissions (143 g ha^{-1}), while in 2016 they tended to be the same (82 g ha^{-1} and 81 g ha^{-1} respectively). However, cumulative CH_4 emissions tended to be lower in P&F in 2015 (126 g ha^{-1}) and 2016 (74 g ha^{-1}), approximately 8-34 g ha^{-1} less than AGP and approximately 7-17 g ha^{-1} less than HFLC.

In 2015, the YS-GWP from soil GHG's was approximately 114 kg CO_2 equivalent Mg^{-1} yield in AGP, 59 kg CO_2 equivalent Mg^{-1} yield in P&F, and 54 kg CO_2 equivalent Mg^{-1} yield in HFLC (Figure 1.7). In 2016, AGP contributed approximately 50 kg CO_2 equivalent Mg^{-1} yield, while P&F contributed approximately 21 kg CO_2 equivalent Mg^{-1} yield and HFLC approximately 11 kg CO_2 equivalent Mg^{-1} yield. In both years AGP tended to have higher YS-GWP than P&F, both of which tended to have higher YS-GWP than HFLC. In 2015, AGP tended to have around double the YS-GWP compared to HFLC, and in 2016 nearly five times the YS-GWP (AGP = 50 kg CO_2 equivalent Mg^{-1} yield vs HFLC = 11 kg CO_2 equivalent Mg^{-1} yield, Figure 1.7). However, these differences were not significant. Among the three treatments, GHG contribution to YS-GWP decreased approximately half to three quarters from 2015 to 2016.

Discussion

Soil Water Content, Inorganic N and N_2O With Fertigation

Soil microorganisms produce N_2O as a byproduct from nitrification and denitrification (Verhoeven, 2017). Additional soil N_2O is derived from nitrifier-denitrification, hydroxylamine decomposition and chemodenitrification (Zhu-Barker & Steenwerth, 2018). Soil water content influences N_2O production through its impact on O_2 diffusion, C availability, and NO_3^- concentration and physical factors that affect gaseous and solute diffusion and transport through the soil, which are all factors controlling mechanisms of N_2O production (Stanford & Epstein, 1974; Williams et al., 1992). Soil water content in our study was not influenced by fertigation treatment, likely because of the same irrigation distribution system (micro-sprinklers) and irrigation schedules among AGP, P&F, and HFLC (Table 1.2). Generally, increased N_2O from denitrification is associated with soil water content above 70% water filled pore space, and nitrification at lower water filled pore spaces and Θ_v (del Prado et al., 2006; Zhu-Barker & Steenwerth, 2018), but these specific WFPS thresholds depend on soil texture (Schjønning et al., 2003). Peak nitrification rates have been reported in soil water content values ranging from 42% WFPS in rangelands (Franzluebbers, 1999) to 60%-80% WFPS in soil cores from undisturbed arable land along a naturally occurring clay gradient (Schjønning et al., 2003). In all three treatments, the largest peak N_2O fluxes of the year follow fertigation events in May, when the soil temperatures begin to increase as the Mediterranean climate transitions to the dry, warm season. N application by fertigation caused an increase in soil moisture, triggering a N_2O flux as described by Barrat et al. (2021). During these largest peak fluxes, our soil water content remained below 65% WFPS among all treatments (Figure 1.3), suggesting that the predominant mechanism for N_2O evolution was nitrification.

Fertigation with inorganic N provides substrate for mechanisms producing N_2O in soil (e.g. nitrification and denitrification) (Bock et al., 1986; Burford & Bremner, 1975; Wrage et al., 2001). Fertigation relieves limitations for both N substrate and water availability in the orchard soils. When soils are not limited by water, substrate availability is the most limiting factor for microbial N_2O production (Stark & Firestone, 1995). In our study, soil water content and temperatures did not differ among fertigation treatments, suggesting that differences in N2O fluxes after fertigation events can be attributed partly to N substrate availability. Findings from other studies in perennial woody crops suggest that we captured at least some of the peak flux from these events within the first two to three days after fertigation. Schellenberg et al. (Kern County, CA, 2012) reported higher N_2O emissions in California almond orchard soils within 24 hours of fertilizer application (45-67 kg N ha^{-1} per application) when compared to emissions following irrigation only applications. Similarly, application of N fertilizer (31.8 kg N ha-1, UAN 32-0-0) using a drip system in wine grapes revealed peak emissions of approximately 4.5 μg m^{-2} s^{-1} within 24 to 52 hours after application (Greenfield, Monterey County, CA; Steenwerth and Belina, 2010). In our study, P&F and AGP had peak fluxes from 1.5 times to nearly 4 times (respectively) the peak flux in HFLC in 2015 and 2016. In 2015, peak N_2O fluxes coincided with peak soil nitrate (NO_3^- -N) and ammonium (NH_4^+ -N) concentrations (Figure 1.5), suggesting that fertigation events alleviated substrate constraints to microbial N_2O production in our soil. In AGP, the greatest peak N_2O flux coincided with highest NO_3^- -N and NH_4^+ -N concentrations in 2015, when AGP received the largest single application of N fertilizer. In comparison, HFLC consistently received lower applications of N per event, indicating that N_2O production in HFLC may have been limited by available substrate, and that reducing the quantity of N substrate can reduce peak N_2O production in the orchard soil.

Yields and N_2O Emissions in HFLC

High frequency fertigation has been evaluated in annual crops but is not well understood as a nutrient program for woody perennial crops such as almonds (cf. Abdelraouf & Ragab, 2018; Assouline et al., 2006; Farneselli et al., 2015; Rajput & Patel, 2006; Silber et al., 2003; Thompson et al., 2003). There are few studies on effects of increased fertigation frequency on yields in orchards, particularly using micro-sprinkler irrigation. Incorporating HFLC as a fertilizer management practice has increased yields in wheat and lettuce, while no significant impact on yields was observed in processing tomatoes or red onions (Abdelraouf & Ragab, 2018; Farneselli et al., 2015; Rajput & Patel, 2006; Silber et al., 2003). Similar to observations by Farneselli et al. (2015) and Rajput & Patel (2006), yields in our study were not impacted by the fertilizer management strategies (Figure 1.2). However, both of those studies were conducted on an annual row crop using drip irrigation. In pomegranates, high frequency subsurface drip fertigation provided sufficient N for trees to achieve optimal yields, while yield in an apple orchard was not impacted by reduced frequency of drip irrigation providing the same total quantity of water (every other day compared to everyday) (Fentabil et al., 2016; Tirado-Corbalá et al., 2019). Our findings and those of others suggest that increasing the frequency of fertigation events, but applying the same total annual N, has a neutral effect on yields in various crops. Furthermore, almond yields in our treatments ranged from 2658 kg/ha to 2833 kg/ha in 2015 and from 2724 kg/ha to 2987 kg/ha in 2016, which tended to be higher than the average almond yield for Madera County during 2015 (2105 kg/ha) and 2016 (2233 kg/ha) (Almond Board of California, 2017).

One study in particular provides a good comparison for our work. Schellenberg et al. (2012) assessed YS-GWP from fertigation of an orchard planted in Milham sandy loam (Fine-loamy, mixed, superactive, thermic, Typic Haplargids) fertilized with UAN 32 and CAN 17. They applied 224 kg N ha^{-1} of annual N fertilizer, split into four applications, through micro-sprinklers. They observed peak emission of 37.1 g N_2O-N ha^{-1} day^{-1} from UAN fertilizer application. In 2015 we observed peak N_2O emissions in our HFLC treatment of 56.3 g N_2O-N ha^{-1} day^{-1}, nearly 1.3-fold greater than the 37.1 g N_2O-N ha^{-1} day^{-1} peak Schellenberg et al. (2012) observed (UAN treatment) when our application rates were lower but both studies had similar total applied N each year (Schellenberg et al. applied a rate 45-67 kg N ha^{-1}, our HFLC applied at most 12 kg N ha^{-1}). The peak flux from AGP in our study that year (2015, 78 kg N ha^{-1} event application) was more than five times that observed by Schellenberg et al. (2012) (212 g N_2O-N ha^{-1} day^{-1} from AGP vs. 37.1 g N_2O-N ha^{-1} day^{-1} from Schellenberg et al. 2012)). However, Schellenberg et al. peak emission was more than double our peak emission with HFLC in 2016 (17.2 g N_2O-N ha^{-1} day^{-1}), but just over half our AGP peak emissions that year (64.0 g N_2O-N ha^{-1} day^{-1}) in 2016. Among our study and many in the literature, a trend in reduced total annual N_2O emissions from more frequent application of N fertilizer but with the same annual fertilizer N totals as in 'standard practices' tends to emerge. Applying N fertilizer more frequently at lower concentrations than the standard practice (e.g. AGP) leads to decreases in substrate N availability and avoidance of the increase in non-linear emission rates observed under high N substrate concentrations (Shcherbak et al., 2014).

Annual Emissions and Yield-scaled Global Warming Potential in Woody Perennial Crops

Our study utilized micro-sprinkler irrigation, which has been shown to produce up to 600 g N_2O-N ha^{-1} annually, compared to 1006 g N_2O-N ha^{-1} in drip irrigation under similar conditions (Alsina et al., 2013). Our annual emissions under standard practices (AGP) ranged from 445.2 to 1004 g N_2O-N ha^{-1}, while our high-frequency fertigation treatment (HFLC) ranged from 95.9 to 474.6 g N_2O-N ha^{-1}. Wolff et al. (2017) observed annual emissions from 510 to 1030 g N_2O-N ha^{-1} in their high frequency applications, which is ranges from similar (474.6 vs 510 g N_2O-N ha^{-1}) to more than 10 times (95.9 vs 1030 g N_2O-N ha^{-1}) the annual emissions observed in our high frequency application. Decock et al. (2017) found that under "typical agronomic management" (micro-sprinkler irrigation with 258–280 kg N ha^{-1} $year^{-1}$ applied), a California almond orchard produced 530 to 650 g N2O-N ha^{-1} per season, falling within the range observed in our revised best management practice (AGP). Seasonal emissions of N_2O in almond orchards are subject to high variability due to soil physical, chemical and microbial factors that can influence nitrification and denitrification in the soil systems (Hénault et al., 2012). Regardless, our findings demonstrate that increasing frequency of fertilizer applications does not result in annual N_2O emissions above those observed in other almond orchards. Notably, they tend to fall on the lower end or below the range reported in other similar studies.

In woody perennial crops, very little work has been done to evaluate the efficacy of high frequency fertigation on soil N_2O emissions or YS-GWP. In one study, high frequency fertigation and irrigation emerged as a potential control for reducing groundwater leaching in almond and pistachio orchards, particularly as an alternative to flood irrigation (Baram et al., 2016). In another study, high frequency fertigation with nitrate-based fertilizers reduced N_2O losses by about half compared to ammoniacal fertilizer; further, leaching losses could be reduced nearly 14 times with high frequency fertigation in comparison to standard practices (Wolff et al. 2017). However, Wolff et al. (2017) saw no significant difference in N_2O emissions between high frequency (20 events) application of ammoniacal fertilizer and standard frequency (4 events) application. Our N_2O emissions in 2015 also did not differ among treatments, however in

2016, N_2O emissions from our standard application of ammoniacal fertilizer (AGP) over six events were 4.5 times greater than from 18 HFLC applications of the same fertilizer type. The difference between treatments in 2016 corresponded with lower emission trends across all treatments relative to 2015, perhaps related to the increase in fertigation events implemented by the grower in 2016.

YS-GWP has been used as a metric for qualifying global atmospheric impacts with economic yields to better understand the value of different management practices. We observed YS-GWP ranging from 114 kg CO_2 eq Mg^{-1} in the AGP treatment, 59 kg CO_2 eq Mg^{-1} in the P&F treatment, and 54 kg CO_2 eq Mg^{-1} in HFLC during 2015 to 50 kg CO_2 eq Mg^{-1} in AGP, 21 kg CO_2 eq Mg^{-1} in P&F, and 11 kg CO_2 eq Mg^{-1} in HFLC during 2016. In another California almond orchard, Schellenberg et al. (2012) observed YS-GWP of 60.9 and 91.9 kg CO_2 eq Mg^{-1} depending on the nitrogen source (CAN and UAN respectively). Our standard application of UAN resulted in approximately similar YS-GWP in 2015, and nearly half that in 2016. Our HFLC application of UAN in 2015 resulted in almost half of what Schellenberg et al. (2012) reported for UAN, and in 2016 our HFLC of UAN resulted in nearly ten-fold lower YS-GWP. Illustrating both the potential of HFLC to decrease YS-GWP, as well as the heterogenous nature of soil evolved GHGs and orchard yields, both of which are largely influenced by edaphoclimatic factors.

Limitations

Our research provides a novel investigation into the specific use of a high frequency fertigation management program in a woody perennial crop. Our results provide support for the capability to reduce YS-GWP and control N losses to the atmosphere specifically by utilizing an

HFLC approach, but also demonstrate the challenge of elucidating impacts in heterogeneous cropping systems. In the second year (2016), the number of fertigation events increased yet annual total N applied remained similar to 2015. As such, the applied N rate per event decreased. In comparison to 2015, peak emissions in 2016 were approximately one quarter of those seen in 2015 across all three treatments (Figure 1.6), although it was not possible to test for effect of year. The ability for producers to increase the number of fertigation events and decrease the concentration of N fertilizer in each event, without changing fertilizer type or sacrificing marketable yields, could provide a tenable strategy to reduce perennial-based agriculture GHGs. However, the variation in influential factors driving the production of GHGs and crop yields, require further investigation to strengthen our understanding. In future studies, increasing the number of years for data collection would clarify lasting impacts of these fertigation practices on soil derived GHG's and YS-GWP.

Conclusion

There is potential for fertigation management to provide an opportunity for agricultural production to reduce greenhouse gas emissions. The results of this study show that the timing and rate of N fertilizer application may provide for a significant reduction in YS-GWP in California almond production. This indicates that a real reduction in cumulative GHG emissions from perennial crop production may be achieved by adjusting fertigation practices, in addition to other management choices. Schellenberg et.al. (2012) showed that the type of fertilizer may not have a significant effect on YS-GWP in California almonds, but with the results of this study, future work may be able to further investigate the effects of varied N sources on YS-GWP using the HFLC technique. This insight could more clearly define N best management practices in almonds and perennial crop production, as it is likely N losses to groundwater leaching would be reduced as well with more frequent applications smaller amounts of N.

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Tables and Figures

Table 1.1 Average N mass balance for each treatment during 2015 and 2016 growing seasons.

	AGP		P&F		HFLC	
	2015	2016	2015	2016	2015	2016
Input Applied (kg-N ha^{-1})						
Fertilizer	257	334	201	224	201	222
Compost	45	0	45	0	45	0
Output (kg-N ha^{-1})						
N-in kernel*	116	108	124	135	118	114
N-in wood	28	28	28	28	28	28
Hull and shell	66	96	71	122	67	109
Loss	91	101	23	0	33	0
Nitrogen use efficiency	0.70	0.70	0.91	>1	0.87	>1

Table 1.2. Analysis of Variance (ANOVA) for effects of fertigation treatment, date of sampling, and the interactions of these on N_2O flux, soil volumetric water content, and soil temperature

Effect	F-statistic	P value	Significance*
2015			
N_2O flux			
Treatment	2.2222	0.1099	n.s.
Sampling Date	35.6106	5.878e-09	< 0.001
Treatment × Sampling Date	2.2132	0.1109	n.s.
Soil Temperature			
Treatment	0.0459	0.9551	n.s.
Sampling Date	110.7373	< 2e-16	< 0.001
Treatment × Sampling Date	0.0496	0.9516	n.s.
Soil Volumetric Water Content			
Treatment	1.6169	0.1993	n.s.
Sampling Date	376.0247	< 2e-16	< 0.001
Treatment × Sampling Date	1.6636	0.1903	n.s.
2016			
N_2O flux			
Treatment	4.5132	0.0118	< 0.05
Sampling Date	74.0308	6.416e-16	< 0.001
Treatment × Sampling Date	4.4457	0.0126	< 0.05
Soil Temperature			
Treatment	0.0459	0.9551	n.s.
Sampling Date	110.7373	< 2e-16	< 0.001
Treatment × Sampling Date	0.0496	0.9516	n.s.
Soil Volumetric Water Content			
Treatment	1.6169	0.1993	n.s.
Sampling Date	376.0247	< 2e-16	< 0.001
Treatment × Sampling Date	1.6636	0.1903	n.s.

* n.s. = not significant

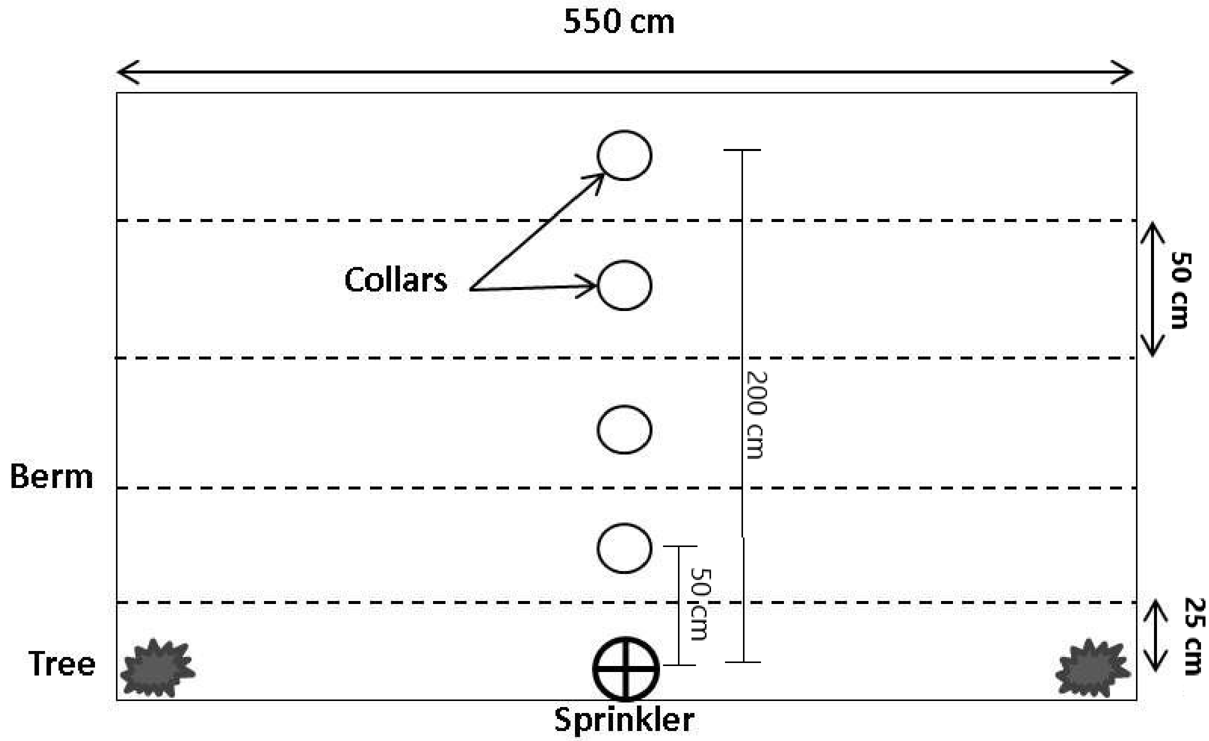


Figure 1.1. Collar Placement within berm and alleyways from micro-sprinkler. Illustrating collar orientation and distances from sprinkler's emitter.

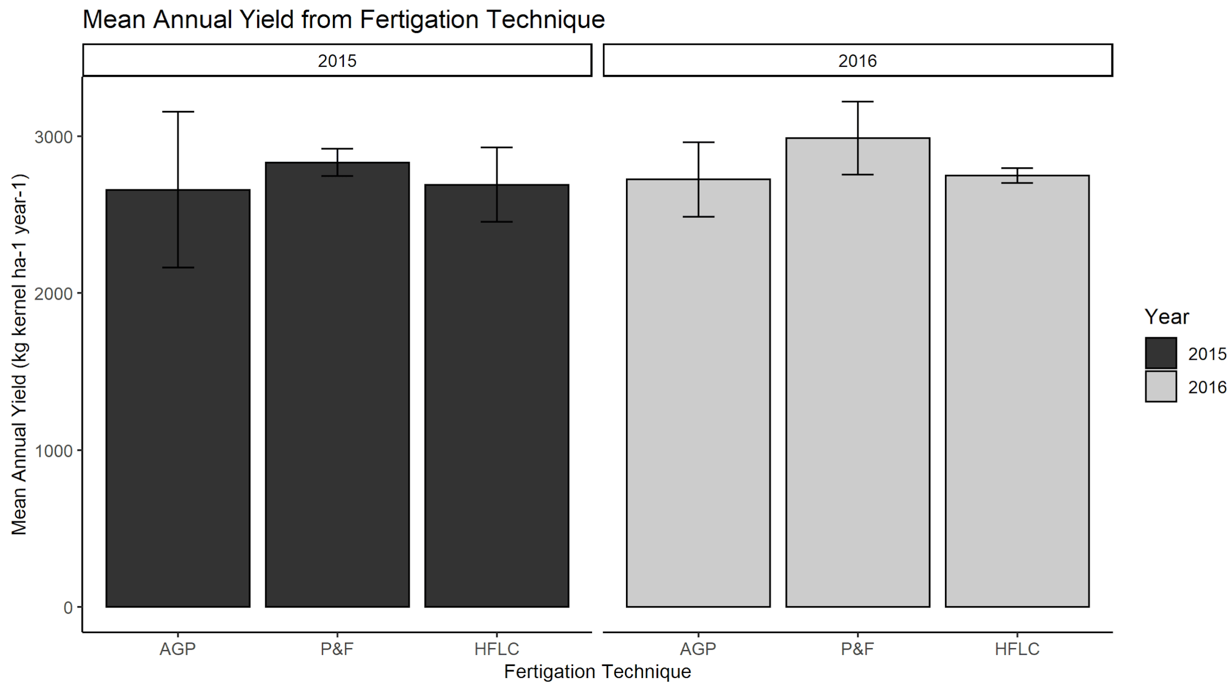


Figure 1.2: Mean annual yield in each treatment for the 2015 and 2016 growing seasons. Analysis of variance through linear modeling indicates no significant effect on yield from treatment (F-statistic = 1.2031, P value = 0.3340), growing season (F-statistic = 0.5494 , P value = 0.4728), or an interaction between them (F-statistic 0.0610 , P value = 0.9411).

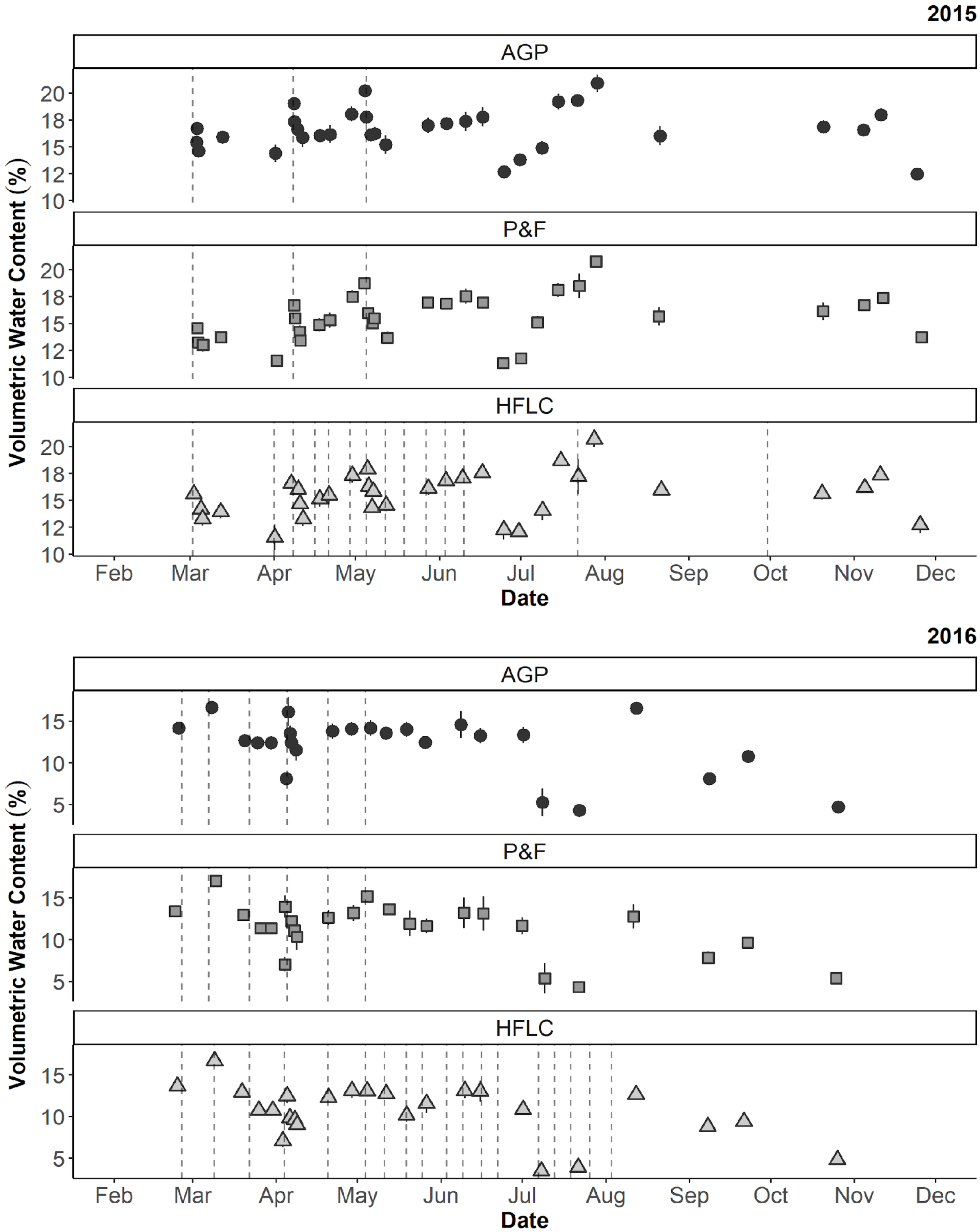


Figure 1.3: Seasonal pattern of soil volumetric water content (Θ_v) at sampling events in 2015 (top) and 2016 (bottom). The circles (Advanced Growing Practices), squares (Pump & Fertigate), and triangles (High Frequency Low Concentration) represent average Θ_v (mean ± SE, n=4), the dashed vertical lines represent fertigation event dates

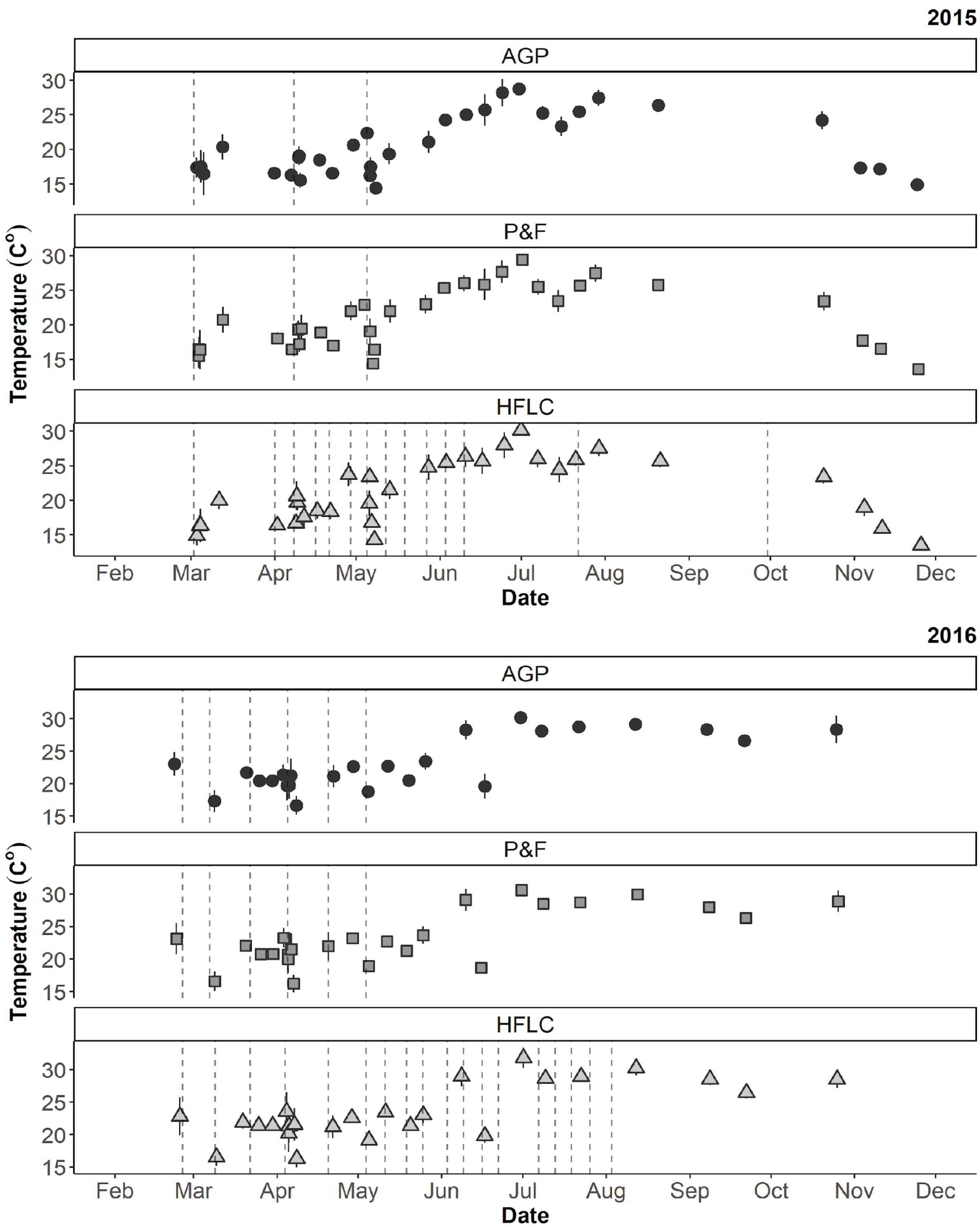
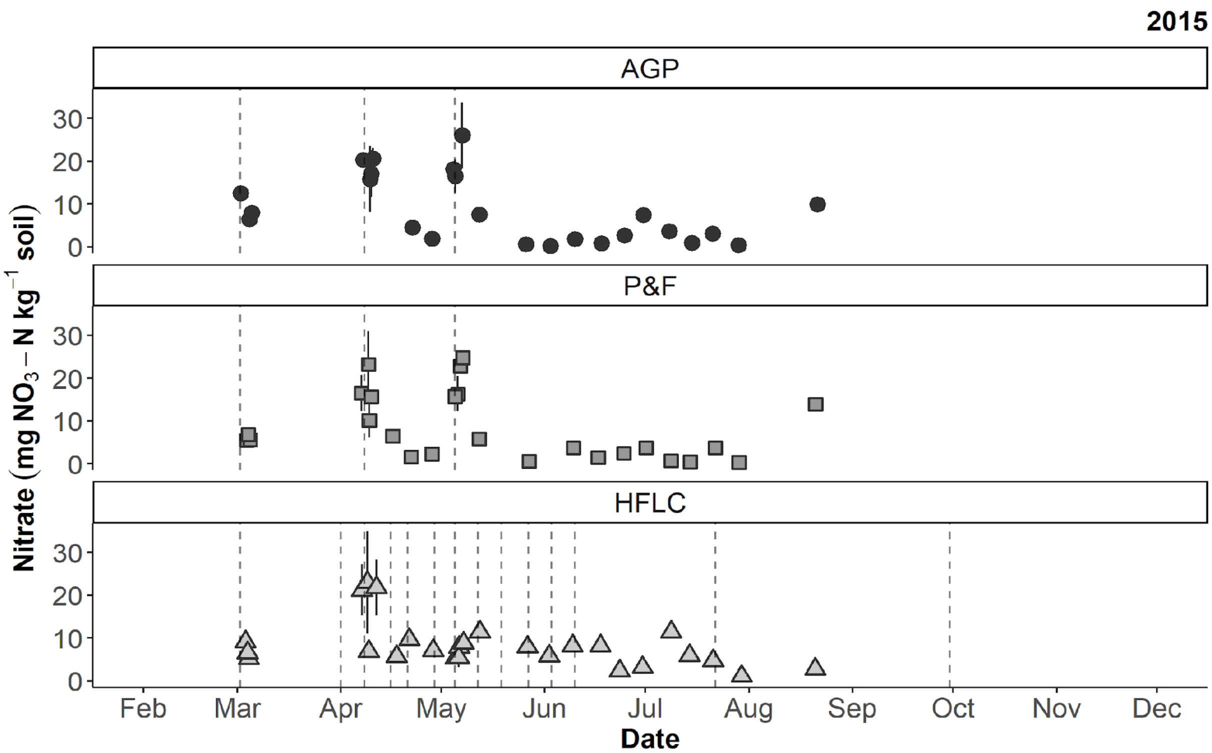


Figure 1.4: Seasonal pattern of soil temperature (℃) at sampling events in 2015 (top) and 2016 (bottom). The circles (Advanced Growing Practices), squares (Pump & Fertigate), and triangles (High Frequency Low Concentration) represent average ℃ (mean ± SE, n=4), the dashed vertical lines represent fertigation event dates.



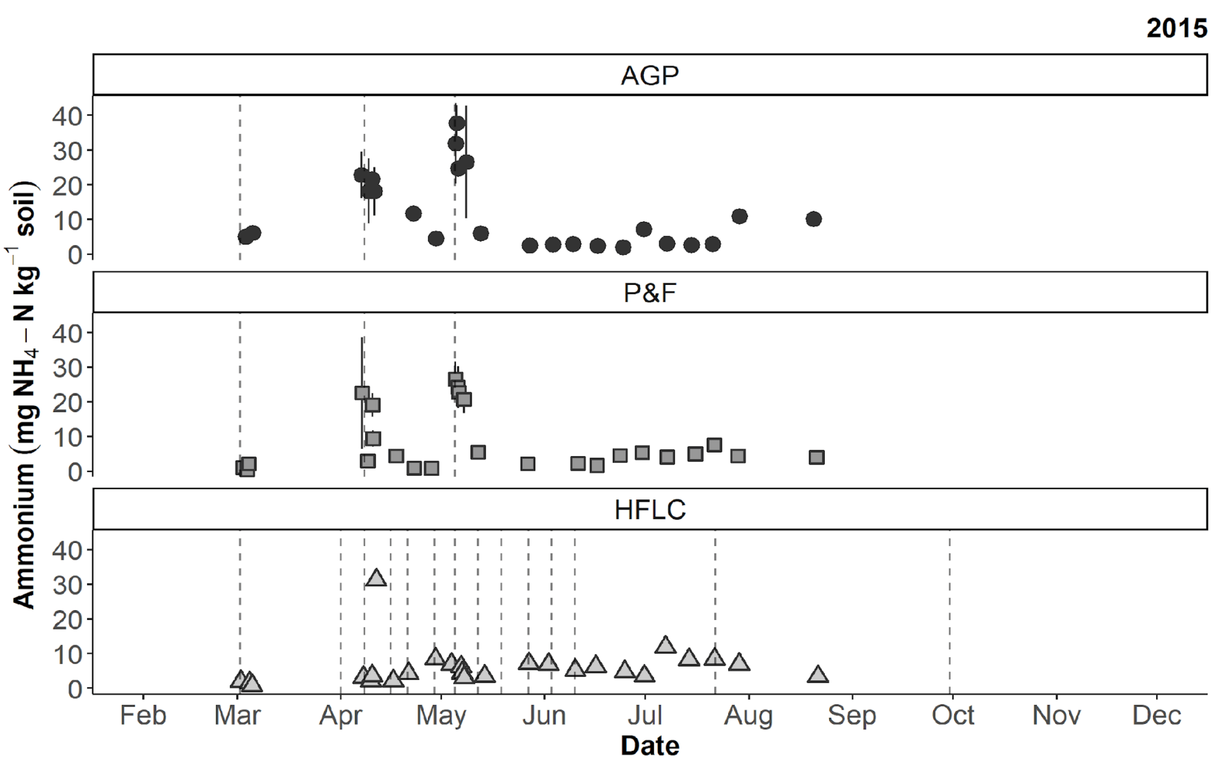


Figure 1.5: Seasonal pattern of soil nitrate (NO_3^- -N) concentration (top) and ammonium (NH_4^+ -N) concentration (bottom) at sampling events. The circles (Advanced Growing Practices, AGP), squares (Pump & Fertigate, P&F), and triangles (High Frequency Low Concentration, HFLC) represent average concentrations (mean ± SE, n=4), the dashed vertical lines represent fertigation event dates.

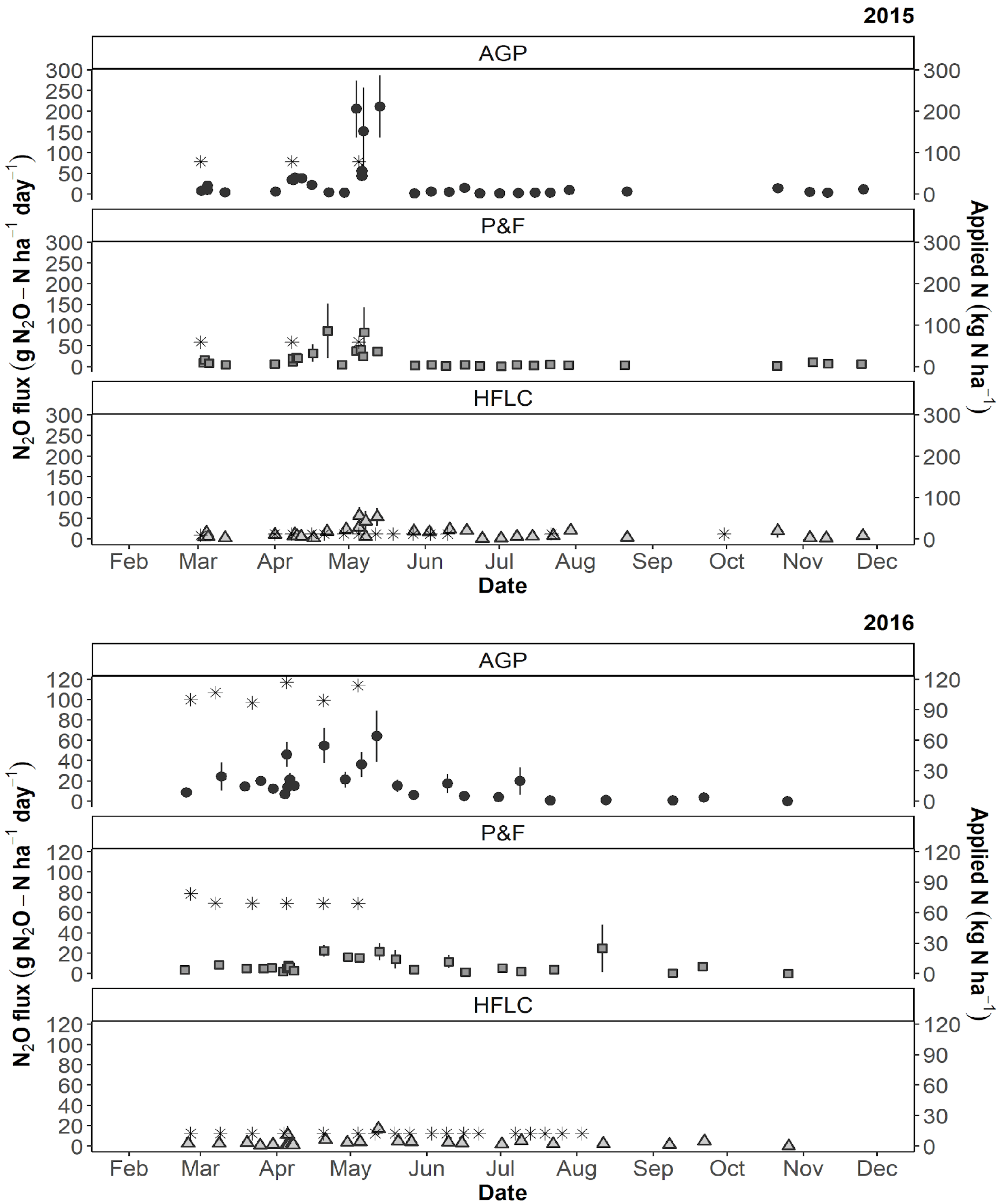


Figure 1.6: Seasonal pattern of N_2O emissions and fertigation events in 2015 (top) and 2016 (bottom). The circles (Advanced Growing Practices), squares (Pump & Fertigate), and triangles (High Frequency Low Concentration) represent average daily N_2O flux (left axis) (mean ± SE, n=4), the '∗' represent fertigation event dates and quantity of fertilizer nitrogen added (right axis).

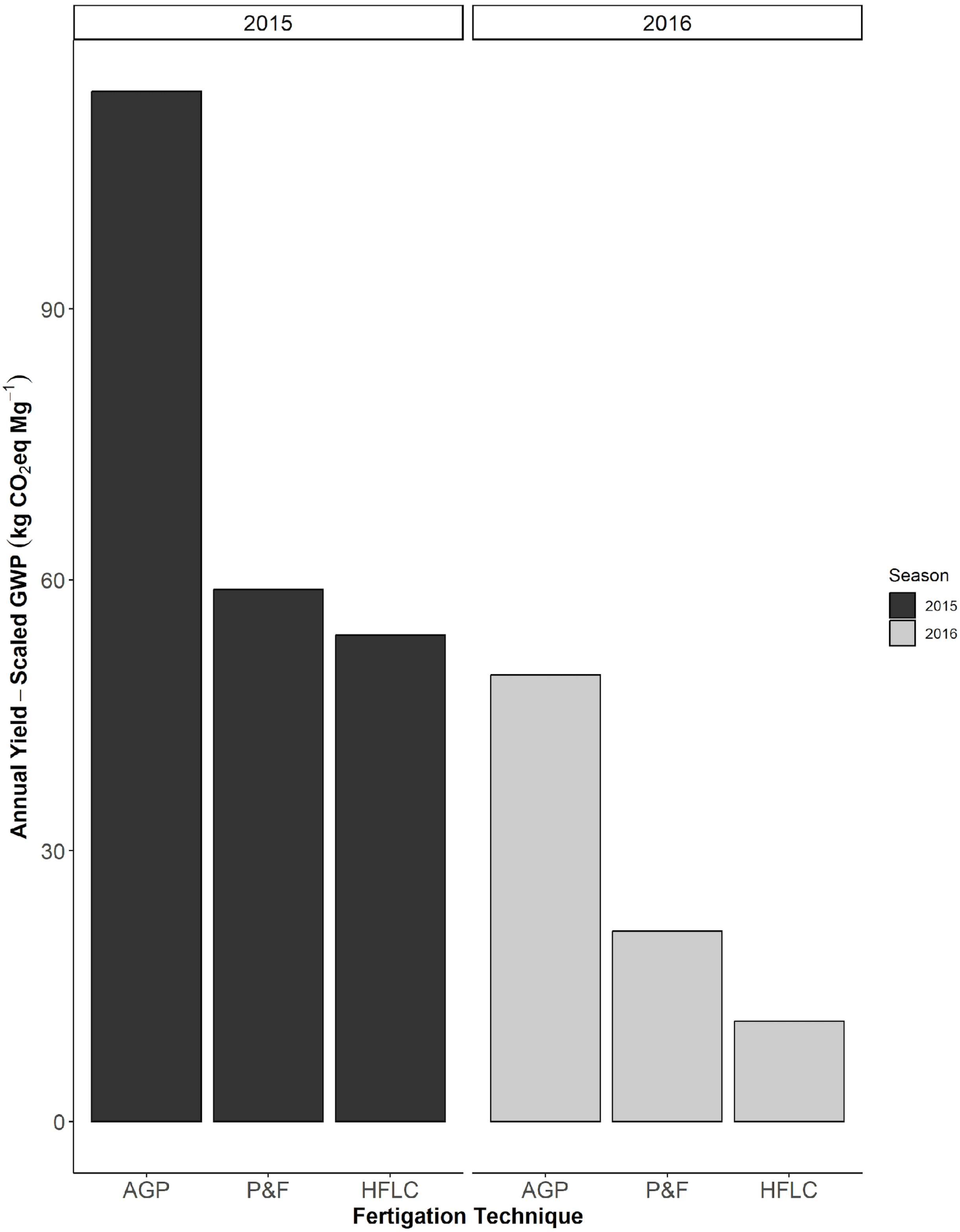


Figure 1.7: Total annual yield scaled global warming potential contribution from each treatment for the 2015 and 2016 growing season. No significant differences were observed between fertigation techniques ($p > 0.05$).

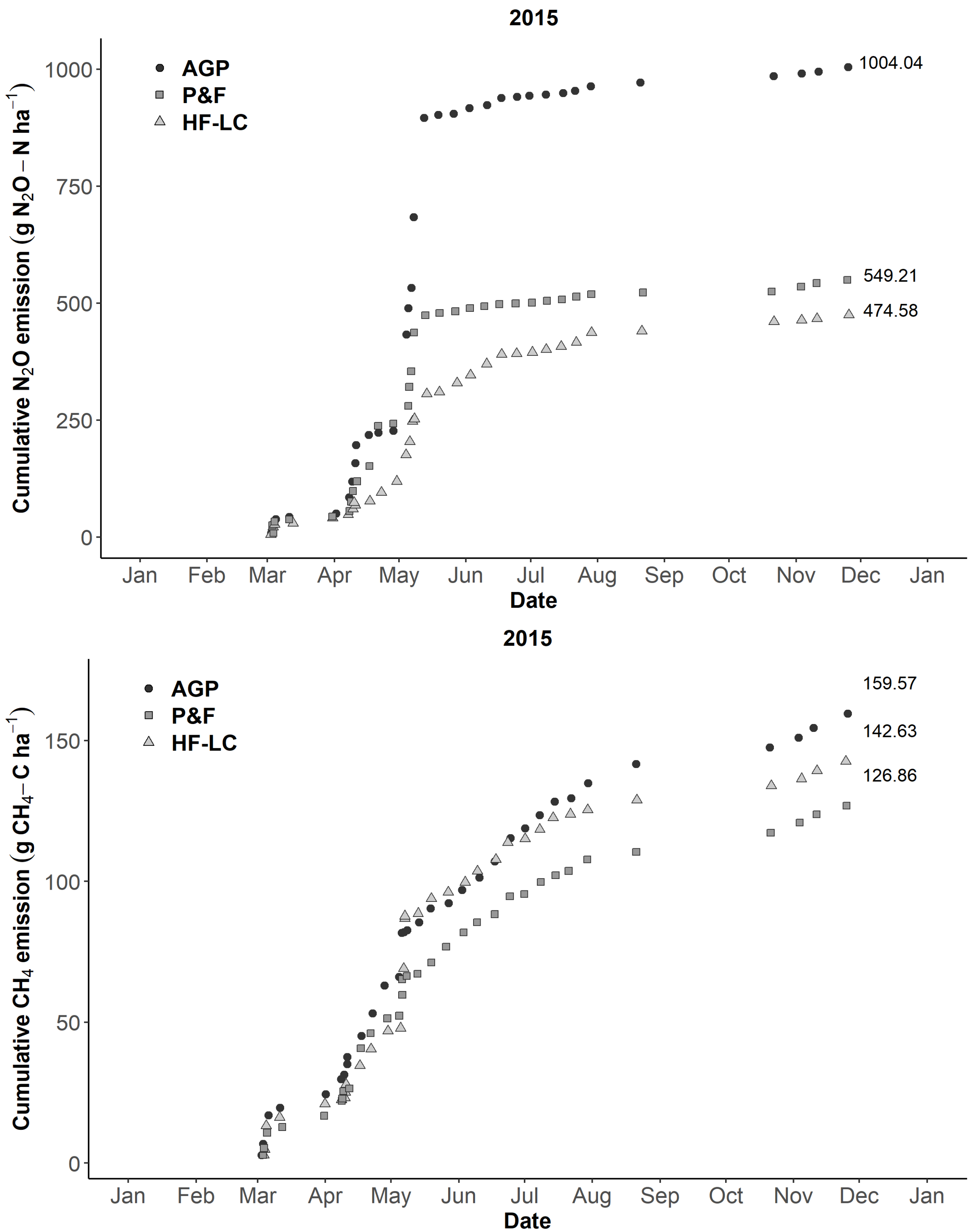
Supplemental Figures

Supplemental Table 1.1. Cumulative total N_2O emissions from treatments, calculated from measured daily means.

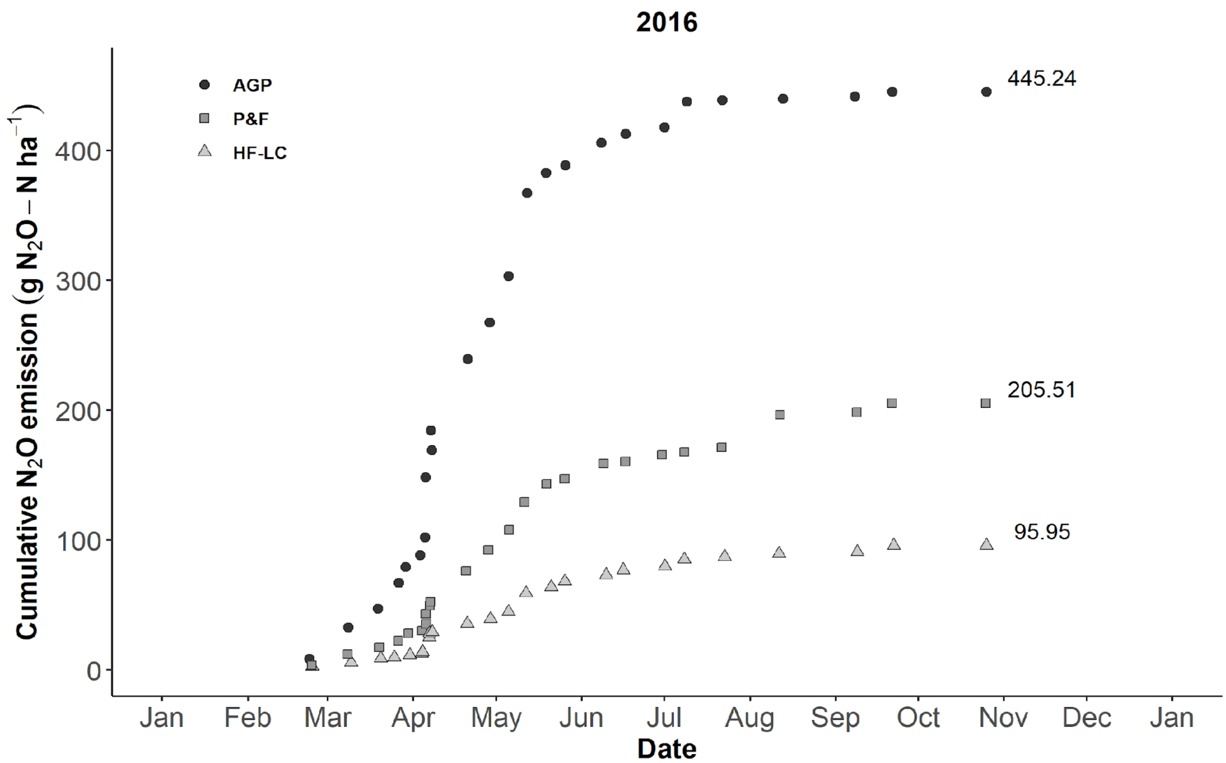
Season	Treatment	Cumulative N_2O-N (g ha^{-1})
2015	AGP	1004.0
2015	P&F	549.2
2015	HFLC	474.6
2016	AGP	445.2
2016	P&F	205.5
2016	HFLC	95.9

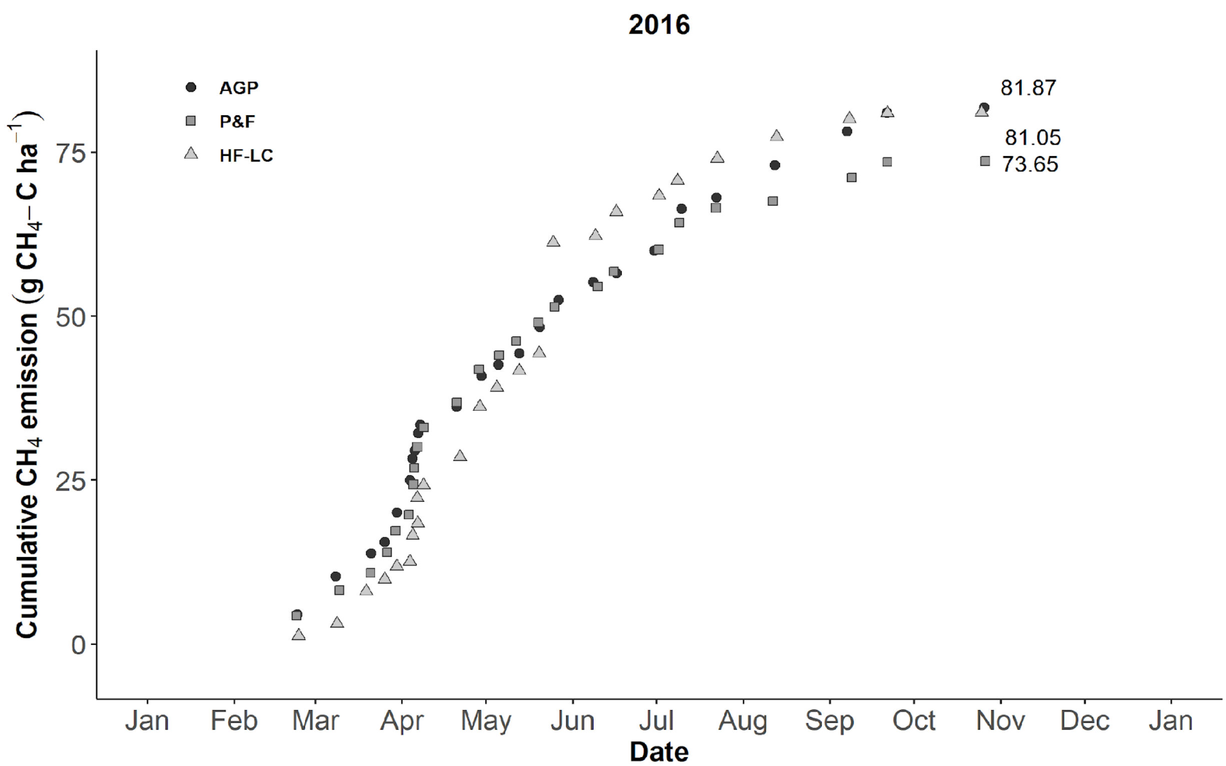
Supplemental Table 1.2. Cumulative total CH_4 emissions from treatments, calculated from measured daily means.

Season	Treatment	Cumulative CH_4-C (g ha^{-1})
2015	AGP	159.57
2015	P&F	126.86
2015	HFLC	142.63
2016	AGP	81.87
2016	P&F	73.65
2016	HFLC	81.05



Supplemental Figure 1.1: Cumulative N_2O (top) and CH emissions (bottom) in 2015. The circles (Advanced Growing Practices), squares (Pump & Fertigate), and triangles (High Frequency Low Concentration) represent cumulative daily N_2O flux (left axis) (mean ± SE, n=4).





Supplemental Figure 1.2: Cumulative N_2O (top) and CH emissions (bottom) in 2016. The circles (Advanced Growing Practices), squares (Pump & Fertigate), and triangles (High Frequency Low Concentration) represent cumulative daily N_2O flux (left axis) (mean ± SE, n=4).

Dissertation Chapter 2
Title: Dynamics of applied Nitrogen during High Frequency-Low Concentration fertigation in a California almond orchard

Patrick K. Nichols
May 21, 2021

Introduction

Perennial cropping systems are being planted on increasing acreage in California. Almond orchards added more than 48 thousand hectares (ha) from 2016 to 2018, totaling over 560 thousand ha (CDFA, 2020). Studies indicate mature almond orchards in California use 224-309 kilograms of nitrogen per hectare (kg N ha^{-1}) annually as fertilizer input in order to ensure optimal fine root production, leaf canopy and economically viable yields (Kendall et al., 2015; Khalsa et al., 2016, 2020a; Muhammad et al., 2015). In orchards, N fertilizer and irrigation are the dominant causes of soil generated greenhouse gas (GHG) emissions. Floor management practices such as tillage, cover cropping, compost application, as well as the irrigation and fertilizer distribution system may have a significant influence on these emissions, particularly in organic Mediterranean fruit tree orchards (Aguilera et al., 2015; Kendall et al., 2015). Irrigation with micro sprinkler systems is increasingly common in orchard systems, as is the application of N fertilizer through these micro sprinkler systems, known as fertigation (Lopus et al., 2010). In vineyards, another widely planted perennial in California, GHG emissions have been shown to be controlled by floor management, irrigation and fertilizer applications that are similar to orchards (Calleja-Cervantes et al., 2015; Steenwerth & Belina, 2008; Yu et al., 2017). While orchard floors may release carbon-based GHGs (CO_2 and CH_4), they are generally considered offset by the high primary productivity and associated CO_2 fixation by orchard cropping systems during their long life span (~25 years), so the focus of GHG (Linquist et al., 2012; Marvinney et al., 2015; Smith et al., 2007).

Nitrogen losses from orchards occur as GHG emissions in gaseous forms (e.g., nitrous oxide [N_2O], oxides of nitrogen [NO_x], dinitrogen [N_2]) and other offsite transport of reactive nitrogen (NH_4^+, NO_3^-, NH_3). These losses are facing increased regulatory scrutiny due to negative impacts on air quality, climate, and drinking water quality (Galloway & Cowling, 2002). Soil derived nitrogen gasses in agriculture are mainly a result of manure from animal systems and the use of N fertilizers in cropping systems (Bouwman et al., 2002; Stehfest & Bouwman, 2006). Fertilizers provide available N to the soil system, and irrigation provides water during naturally dry periods, particularly in climates with minimal precipitation during the growing season. In almond orchards, soil water content and nitrogen availability are a function of fertigation practices and are generally responsible for N_2O production by driving nitrification and denitrification processes (Smart et al., 2011).

Nitrous oxide production in soil is generally considered a byproduct of the enzymatic processes of nitrification and denitrification (Verhoeven et al., 2017; Wrage et al., 2001). Nitrification is the oxidation of ammonium (NH_4^+) or ammonia (NH_3) to nitrite (NO_2^-) and then nitrate (NO_3^-) (Zhu-Barker & Steenwerth, 2018). Denitrification can be coupled with nitrification, during which NO_3^- and NO_2^- from nitrification is reduced to molecular nitrogen (N_2) gas, producing N_2O as an intermediate. Denitrification also occurs by nitrifier denitrification reducing NH_3 to NO_2^- to nitric oxide (NO), nitrous oxide (N_2O) and (N_2) (Zhu-Barker & Steenwerth, 2018). These pathways, mediated by microbes and fungi, can simultaneously produce N_2O in soil depending on soil conditions.

Soil water content (or water filled pore space) is largely in control of oxygen availability in the soil, and microbial activity can also play an important role through the consumption of oxygen and respiration of carbon dioxide (CO_2) (Sylvia et al., 2005). Nitrogen processes are influenced by soil oxygen levels, as nitrification requires the presence of oxygen while denitrification is favored in low oxygen concentrations (Verhoeven et al., 2017; Zhu et al., 2013). Soil oxygen and soil water are mostly confined to the same physical space in soil (the pores) and can be viewed as inversely proportional. Pore characteristics, such as volume, size, and associated tortuosity of flow paths, impact movement and exchange of soil water and thus emissions of gaseous N (Khalil & Baggs, 2005). Nitrogen emissions can correlate positively with water filled pore space in agricultural soils (Khalil & Baggs, 2005; Verhoeven et al., 2017). Pore characteristics are partially a function of the soil physical factors of bulk density and texture (Brady & Weil, 2010), which could provide correlating indicators for potential N_2O production in soil.

Not all N_2O is from biological pathways. a portion of soil N_2O production is attributable to abiotic factors such as hydroxylamine decomposition (Zhu-Barker et al., 2015). In addition to porosity, texture and moisture, other soil characteristics (i.e. temperature, substrate availability, pH) regulate abiotic process and biological pathways of N_2O production in soil (Azam et al., 2002; Stevens et al., 1998; Zhu et al., 2013; Zhu-Barker & Steenwerth, 2018). Temperature is a key driver of microbial activity in general, while availability of substrates such as NH_4^+, NO_3^- and soil carbon (C) may regulate microbial productivity. Soil pH can influence N processing, resulting in high NO_2^- accumulation as decreased pH can promote the formation of nitrous acid, inhibiting both steps of nitrification (Hunik et al., 1992, 1993; Venterea & Rolston, 2000). Influence on substrate availability by decreased soil pH can inhibit NH_4^+ oxidation, and reduced pH potentially enhances end-product inhibition of NO_2^- oxidation (Hunik et al., 1993; Prosser, 1990). Impact of pH on soil nitrogen dynamics is dependent upon other soil characteristics. Venterea and Rolston (2000) identified critical values of pH, below which the NO_2^- oxidation is significantly inhibited, were consistent within three soil types but different between them (Venterea & Rolston, 2000).

Soil physical characteristics (such as texture, structure, and porosity) and chemical characteristics (such as pH, C and N content) are highly variable at scales ranging from microscopic to landscape. Spatial heterogeneity of soil water content, soil organic matter, temperature and inorganic N pools create "hot spots" and "hot moments", during which peak reaction rates result in higher production of N_2O relative to the greater local pattern (McClain et al., 2003). Soil N_2O emission vary spatially because of heterogeneity in soil characteristics and vary temporally with changing conditions within soil characteristics (Bouwman, 1996). The influences range from microbial dynamics in the soil pores to soil surface management decisions, to local microclimates and the climate at large (Zhu-Barker & Steenwerth, 2018). Hence, wide variability of soil N_2O production is attributable to the heterogeneity of soil characteristics and the confluence of abiotic and biotic circumstance, influenced by temporal conditions.

Availability of substrates is a known control for soil N_2O production, and application rates of N fertilizers (substrates for N_2O) can impact annual emissions (Stehfest & Bouwman, 2006). Fertilizer application rates targeting crop nutrient demand can optimize yield-based emission totals in non-leguminous annual crops (Van Groenigen et al., 2010). Implementation of N fertilizer programs customized for perennial cropping systems that focus on physiological demands during various growth stages, could provide similar optimization for large commodity sectors (Muhammad et al., 2015). The use of high frequency applications of a low concentration of fertilizer (HF-LC) may provide an important strategy for reducing annual N_2O emission in agricultural sectors by reducing inorganic N pools to specific amounts needed by the crops, and thus reducing the magnitude and duration of peak emissions following N fertilizer applications. Studies of high frequency fertigation methods have been conducted mostly in non-perennial crops, in greenhouses and field rows (Abdelraouf & Ragab, 2018; Assouline et al., 2006; Farneselli et al., 2015; Rajput & Patel, 2006; Silber et al., 2003; Thompson et al., 2003). Increased fertigation frequency has been effective at reducing losses of applied nutrients in annual crops, with improved uptake and reduced leaching in lettuce, onion, tomato, bell pepper, as well as wheat when modeled or grown in field (Abdelraouf & Ragab, 2018; Assouline et al., 2006; Farneselli et al., 2015; Rajput & Patel, 2006; Silber et al., 2003). Under high frequency fertigation, many of these crops had yield increases and improved N use efficiency (NUE). However, in a subsurface drip irrigation system with high frequency fertigation, broccoli grown in a sandy loam soil showed little response in NUE or yield with high frequency events (Thompson et al., 2003). Additionally, pulsed fertigation at a very high frequency (multiple events a day) in bell peppers showed potential salinity issues (Assouline et al., 2006).

In woody perennial crops, little work has been done to evaluate the efficacy of a high frequency fertigation management program. In one study, high frequency fertigation and irrigation was identified as a potential control for reducing groundwater leaching in almond and pistachio orchards, particularly as an alternative to flood irrigation (Baram et al., 2016). Another study in almonds concluded high frequency fertigation with nitrate-based fertilizers significantly reduced N_2O losses compared to ammoniacal fertilizer and indicated that leaching losses could be reduced with high frequency fertigation compared to standard practices (Wolff et al., 2017).

In our previous work, HF-LC significantly reduced annual N_2O emissions and yield scaled global warming potential in California almond orchard (Nichols et al., unpublished).

The influence of fertigation and soil management practices on soil N dynamics and gaseous N fluxes from orchard soils are poorly understood in California almond production. Scaling N_2O emissions across landscape scales such as orchards is limited by the heterogeneity of N_2O fluxes, and a poor understating of the influence soil heterogeneity, management decisions, and changing soil conditions. To achieve a greater understanding of these processes, our study examined the influence of an almond fertigation strategy (HF-LC) designed to reduce the loss of applied nutrients (N) on soil derived greenhouse gases (namely N_2O). We analyzed HF-LC at an orchard scale, and how the variability of the soil and irrigation distribution might translate into flux estimations. We evaluate the variability of GHG emissions with respect to soil physicochemical factors under HF-LC fertigation management strategy. We also quantify relationships between soil inorganic N and gaseous N fluxes with high frequency N input at low concentrations. Specifically, we hypothesized: (1) HF-LC fertigation will likely impact soil N dynamics, decreasing losses as gaseous N from the orchard floor; (2) variability in GHG emissions in an almond orchard will be partially explained by soil physicochemical characteristics; (3) soil inorganic N will have a direct correlation with gaseous N fluxes.

Methods

Research site

This research was conducted on a 56-hectare almond orchard, located approximately 8 km west of Modesto, California (37°37'38.17" N 121° 5'21.57"W). The site is comprised of four orchard blocks (orchards) planted with Nonpareil, Fritz, Aldrich and Carmel varieties. Trees range in age from 8-23 years, with younger replanted trees interspersed to replace fallen or removed individuals. Maximal rooting depth of the almond orchard was determined to be near three meters, with > 90% of the fine roots within the first meter (Baram et al., 2016). This research site is part of a long-term study focused on nitrogen (N) transfers in the soil vadose zone. The orchards' soils are mapped as three soil series (Table 2.1) which are well to moderately well drained and composed of alluvial deposits. The location in California's Central Valley is considered a semi-arid climate, characterized by warm, dry summers and cool winters. Annual precipitation averages 33.3 cm, most of which occurs from December to March, with average summer monthly temperatures ranging from16°C to 34°C and average winter monthly temperatures ranging from 5°C to 14°C (California Irrigation Management Information System [CIMIS], url: http://www.cimis.water.ca.gov).

Tree spacing in the orchards ranges from 4.3 m to 7 m, with fan jet micro-sprinkler irrigation (Table 2.2). Fertilizer was applied in soluble form through the irrigation using a computer-controlled precision irrigation system (pH Technologies LLC). The computer system facilitated the grower's use of an innovative fertigation technique of high-frequency applications with low concentrations of fertilizers. This technique resulted in 12-16 applications of N fertilizer, ranging from 2.7 kg to 5.4 kg of N per application. Aside from the HF-LC fertigation technique, the almonds were grown using practices considered standard to the industry in the Central Valley of California.

Soil Sampling

Soil in the orchards was sampled in August 2019 for soil characterization. Samples were collected in each orchard near the chamber array locations, described below, and weighed in the field and transported in aluminum containers to the lab for analysis. Subsamples were used for texture composition using the pipette method (Miller & Miller, 1987). Additional subsamples of soil were weighed and sent to the UC Davis Analytical Lab for pH, EC, total C, and total N.

Gas Sampling and Soil Data

Gas flux rates were measured using the closed chamber method (Livingston and Hutchinson, 1995). Within each orchard, PVC collars were placed in three treatment replicate arrays. Each array consists of five collars placed in a transect perpendicular to the row, at distances of 0cm, 50cm, 100cm, 150cm, and 200cm from fan jet micro sprinkler at the head of the berm to near the center of the alleyway between the tree row (Figure 2.1). Gas samples were taken following fertigation events and periodically during the growing seasons. During the winter months of January-February, no data was collected as no fertigation events occurred and trees were considered dormant. On collection days, static chambers constructed according to Parkin and Venterea (2010) were placed on preinstalled collars 10 minutes prior to gas sampling. Ambient gas samples were collected at time 0, and gas was extracted from chambers at 10 and 20 minutes. For each site, samples of 10 min 20 min intervals were collected for each distance from the emitter along each transect array and one ambient gas sample. All samples were manually extracted from chambers using hypodermic needles and injected into 12 cm^3 evacuated glass vial exetainers (Exetainer®, Labco Limited, Buckinghamshire UK) for transportation. Samples were analyzed in the lab using a gas chromatograph GC-2014 Shimadzu, furnished with a ^{63}Ni electron capture detector for measurement of GHGs. Simultaneous to gas collection, field conditions of volumetric soil water content and soil temperature were collected using a Probe Check Decagon Device. Additionally, soil samples were collected at each treatment, with alternating treatment replicates on each collection day. Soil samples were placed in 2M KCL solution and analyzed for nitrate and ammonium concentrations colorimetrically.

Harvest

The mature almonds were harvested annually from August to October by shaking trees (standard industry practices). Fruit was dried on the orchard floor an average of 10 days, and then swept into windrows and collected by harvester machines when final water content of fruit was approximately 6%. Harvest subsamples within each orchard were taken for mass fraction analysis to determine kernel yield (Muhammad et al., 2015).

Flux and Yield-scaled GWP

Linear regressions of chamber concentration were used to calculate gas flux rates (q) [g cm^{-2} h^{-1}] in addition to the ideal gas law according to:

[1]	$q = \frac{dc_{gas}}{dt} * \frac{V_{chamber}}{A_{chamber}} * \frac{P}{RT} * M_w$

where c_{gas} is the measured gas concentration [µL l^{-1}], t is time [hour], $V_{chamber}$ [cm^3] and $A_{chamber}$ [cm^2] are the chamber volume and surface area respectively, P is the ambient pressure [0.988 atm], R is the gas law constant [0.08206 l atm mol^{-1} K^{-1}], T is the temperature [K], and M_w is the molecular weight of the gas [g mol^{-1}]. Daily flux values were estimated assuming the measured fluxes were the daily average (Schellenberg et al., 2012).

Nitrous oxide emission measurements around the irrigation emitters were upscaled to the orchard level using a unit tree area. The wetted area around a tree can be represented by a circle with a 225 cm wetting radius (distance of emitter distribution). Every chamber measurement would then represent a 50 cm radius wetted ring, the center of which would be represented by the chamber measurements at lesser distances. Thus, the emission estimates are based on a series of concentric rings (except the 0 cm distance) each representing the distance from the emitter at which the flux was measured. The 0 cm measurement represented a 25 cm radius wetted disk directly around the emitter. This approach assumes each measurement position was representative of the gas flux of the wetted area of the circle the emitter deposited at that distance around the emitter. The basis for this assumption was that the wetting pattern around the emitter was two dimensional (Schellenberg et al., 2012). Calculated emissions were then summed and multiplied by the given wetted disk areas to give total N_2O emission per tree:

[2]	$$Q_{tree} = \sum_{i=0}^{r_{max}} \pi q_i (r_{i+x}^2 - r_i^2)$$

where Q_{Tree} is total emission per tree [ng N_2O-N h^{-1}], q_i is the emission rate measured at the i^{th} collar [ng N_2O-N cm^{-2} h^{-1}], *i* is the distance from the emitter (cm), *x* is the width of the wetted disk (cm), following Baram et al., 2018.

Experimental Design

This study was conducted on three orchards on site, all of which utilize fan-jet micro-sprinklers to distribute irrigation and soluble fertilizers (Table 2.3). In orchards 1 and 4 tree plantings and irrigation emitters are installed at distances providing one emitter per tree, with the distribution lines approximately 45 cm below ground in Orchard 4 and not Orchard 1. Irrigation emitter installation and tree plantings in Orchard 3 were designed to provide two emitters per tree. Within each orchard, three treatment replicates of the chamber collar transect arrays were installed (Figure 2.1). As described above, each array represents the flux from the wetted disk around a single emitter. This provides an estimate of flux from one emitter per array, and three replicate emitters per orchard.

Results

Over the course of the 2017 season, the measured daily N_2O fluxes were highest during April, when fertigation applications coincide with warming temperatures and growth in the trees and floor vegetation (Figure 2.2). While CH_4 fluxes were highest in May, CO_2 fluxes were lowest for the season. Orchard 3 generally produced the highest daily N_2O and CO_2 fluxes, with Orchard 4 emitting the highest CH_4 fluxes during 2017. Seasonal daily CH_4 fluxes appear to pattern inversely to daily N_2O fluxes, while seasonal CO_2 fluxes appear to not follow the pattern of CH_4 or N_2O.

During the 2018 season we observe a similar pattern with N_2O, daily fluxes peaking during April with Orchard 3 often having the highest daily fluxes (Figure 2.3). The inverse relationship between N_2O and CH_4 is present to a lesser extent during the 2018 season in comparison to the 2017 season. Orchard 1 had the highest daily flux of CH_4 and CO_2 but is not consistently higher throughout the season for either gas.

The N_2O and CO_2 daily fluxes during the 2019 season were measured highest in Orchard 1, while Orchard 4 produced the highest daily CH_4 measured during the season (Figure 2.4). The inverse pattern between N_2O and CH_4 is apparent in Orchard 4 during the 2019 season, and not as clear in the other orchards. The highest measured daily CO_2 flux during the 2019 season (50.47 kg C-CO_2 ha^{-1} day^{-1}) was approximately 53% higher than the 2018 season (33.06 kg C-CO_2 ha^{-1} day^{-1}) and approximately 19% greater than the 2017 season (42.42 kg C-CO_2 ha^{-1} day^{-1}). However, the maximum measured daily flux of CH4 in 2019 (5.50 g C-CH_4 ha^{-1} day^{-1}) decreased approximately 84% from 2017 and 46% from 2018 (34.50 g C-CH_4 ha^{-1} day^{-1} and 10.23 g C-CH_4 ha^{-1} day^{-1}, respectively). The highest measured daily N2O flux in 2019 (22.65 g N-N^2O ha^{-1} day^{-1}) was approximately 82% lower than 2018 (106.38 g N-N^2O ha^{-1} day^{-1}) and approximately 79% lower than 2017 (128.36 g N-N^2O ha^{-1} day^{-1}).

During the spring (around April and May) temperatures are consistently warmer than the winter months, water is readily available (stored in soil or applied) and fertilizers nutrients are provided, tree physiology is highly active with bloom and leafing out the canopy for the growing season, and orchard floor vegetation is rapidly growing. This part of the season often results in the highest fluxes of N_2O and CO_2, but not necessarily CH_4. During the springtime fluxes, when we see peak N_2O emissions, Orchard 4 emitted the lowest N_2O fluxes during each of the three seasons and the highest spring CH_4 emissions (Figure 2.5). Peak springtime N_2O fluxes alternated between Orchard 1 and 3 during both the 2018 and 2019 season. Orchard 3 produced the highest spring fluxes of CO_2 during 2017 and generally the lowest during 2018 season, with Orchard 1 fluxes exceeding Orchard 3 and 4 during the spring of both the 2018 and 2019 seasons.

Soil temperatures measured during sampling events follow similar patterns during each season (Figure 2.6). However, the orchards with highest measured soil temperatures do not remain consistent within seasons. During the 2017 season Orchard 3 had the highest mean temperature in late spring, while in mid-season Orchard 1 was measured the highest and during the end of the season (near harvest) Orchard 4 recorded the highest mean soil temperature. We see a similar pattern for 2018, during pre-senescence (after the previous season harvest) Orchard 4 soil temperatures are generally higher than Orchard 1 and 3, while in the winter Orchard 3 soil was warmer. This shifts to Orchard 1 being warmer during spring/mid-season, with Orchard 4 again measuring warmer as the 2018 season nears harvest. During the 2019 season, Orchard 1 is warmer in early spring, with Orchard 4 measuring the warmest mid-season but 1 and 3 alternating highest mean soil temperature at the end of the season.

Mean measured soil water content also shows differences between orchards dependent upon the phase of the growing season during which the samples were collected (Figure 2.7). In early spring during the 2017 season, we see Orchard 3 had higher soil water content relative to Orchard 1 and 4. Through mid-season Orchard 4 measured higher soil water content, and as the season approaches harvest Orchard 1 generally measured higher soil water content. For most of the 2018 season, Orchard 1 soil water content was higher than Orchard 3 and 4, however during the spring Orchard 3 had a higher measured water content. Similar to 2018, the 2019 season also recorded higher soil water content in Orchard 1 during the winter early season. As the season progressed Orchard 3 measured higher during early spring then alternating with Orchard 1 during mid-season. However, towards the end of the season nearing harvest, Orchard 4 generally had higher soil water content during the 2019 season.

Soil inorganic N concentrations (represented by the combination of NH_4 and NO_3) fluctuates throughout the seasons (Figure 2.8). It should be noted that inorganic N sampling experienced some technical difficulties resulting in data gaps, thus some sampling days for which we have other data points do not have soil inorganic N concentrations. The largest concentrations of soil inorganic N are often in the spring, when fertilization applications are fairly consistent. During the 2017 and 2018 growing seasons the highest recorded concentrations of inorganic N were sampled during the mid-season springtime and from Orchard 3. During the 2019 season, we recorded higher concentrations in Orchard 1 during the winter early season sampling relative to the high Orchard 3 concentrations sampled during the spring mid-season.

In all three orchards the soil temperature and water content trend inverse of each other, higher temperatures generally have lower soil water content and vice versa (Figure 2.9).

However, the measured data is spread widely and not tightly correlated which could be attributed to the application of irrigation during the warmer months when the soil would naturally be driest.

No strong correlation between soil water content and inorganic N concentrations was observed (Figure 2.10). The highest inorganic N concentrations were measured between 10-30% soil water content, and all 3 orchards appear to have no positive or negative relationship between the two values.

Generally, N_2O fluxes were highest around 20-25 °C, while higher CO_2 fluxes appear to be spread along a greater temperature gradient, approximately 15-30 °C (Figure 2.11). Methane does not appear to be as responsive to soil temperature, however we do see that greater negative fluxes (sinks back into soil) are observed below 25 °C.

In the orchards we observed the highest N_2O fluxes when soil water content was approximately 20-35% (Figure 2.12). The highest CO_2 fluxes were observed between 30-40% soil water content; however, CO_2 emissions were generally distributed more evenly throughout all the measured soil water content values compared to N_2O emissions. Methane emissions were relatively consistent through most soil water content values; however, we observed the greatest positive CH_4 flux (source) and the greatest negative CH_4 flux (sink) around 30-45% soil water content.

The concentration of inorganic N (NH_4 and NO_3) does not appear to directly drive the N_2O fluxes observed in the orchards (Figure 2.13). Although we do see the largest N_2O fluxes occurring when we measured approximately 30-40 mg kg^{-1} soil, it is not significantly higher than fluxes occurring at lesser or greater concentrations of inorganic N. Similarly, no distinct relationship appears with CO_2 fluxes. Although CH_4 also does not have a distinct relationship, the sink fluxes do tend to occur with lower inorganic N concentrations.

The fan jet micro sprinklers at the study site distribute fertigation relatively evenly on the soil surface in an approximate circle commonly with a radius of approximately 200 cm from the emitter. The distance from the emitter does not have a strong influence on the gas fluxes measured (Figure 2.14). Although N_2O fluxes do appear to generally be highest at 0cm and 150cm it is not a distinct pattern. Similarly, the N_2O fluxes at 200 cm from the emitter generally appear to be lower. The amount by which the fluxes at 200 cm differ from the other distances could be considered negligible, even though this is at the edge of the spray pattern. The same is observed with CO_2 and CH_4 fluxes, distance from emitter does not influence the gas fluxes.

Orchard 3 emitted higher total measured N_2O during the 2017 and 2018 seasons, and Orchard 1 during the 2019 season (Figure 2.15). However, during the 2017 season Orchard 1 had the lowest cumulative N_2O emissions, and had emissions between Orchard 3 (highest) and Orchard 4 (lowest) emissions for 2018. Orchard 4 recorded the lowest cumulative emissions for both the 2018 and 2019 seasons.

Cumulative CH_4 emissions were greatest in orchard 4 during the 2017 and 2018 seasons (Figure 2.16). However, during the 2018 growing season a greater amount of CH_4 emissions were recorded in Orchard 3. Orchard 4 recorded the highest cumulative emissions of CO_2 for the 2018 and 2019 seasons, but Orchard 3 emitted more CO_2 cumulatively during the 2017 season (Figure 2.17).

Discussion and Conclusion

Soil Physical and Chemical Properties

Microbial pathways and abiotic processes can simultaneously produce N_2O in soil and are influenced by similar physical and chemical soil factors (i.e. texture, water content, pH, organic matter, and inorganic N). Biotic nitrous oxide production in soil is generally considered a byproduct from nitrification of NH_4^+ or NH_3 to NO_2^- then NO_3^-, and denitrification of NO_3^- to N_2 gas (Robertson and Tiedje, 1987; Verhoeven, 2017). Gaseous nitrogen also results from abiotic soil processes such as hydroxylamine decomposition and chemodenitrification (Zhu-Barker et al., 2015; Zhu-Barker & Steenwerth, 2018). The continuum of oxygen availability in the soil solution often regulates prevalence of N_2O pathways, nitrification requires the presence of oxygen while denitrification is favored in low oxygen concentrations (Venkiteswaran et al., 2014; Verhoeven, 2017). This continuum of available oxygen in our study soil is reflected in Figure 2.12. Sampled fluxes occurred at a range of soil water contents, the fluxes occurring below 20% soil water content likely result from nitrification or a combination of nitrification and denitrification. In our study, peak N_2O emissions were observed during soil water contents ranging from 20%-35% (45%-75% water filled pore space). We observed fluxes when soil water content was in excess of 40%, or 90% water filled pore space, suggesting that abiotic processes like chemodentrification may have occurred under these anoxic conditions (Wang et al., 2020). As soil oxygen and soil water are mostly confined to the same physical space in soil (the pores), they can be viewed as inversely proportional (Linn and Doran, 1984). Therefore, soil water content (or water filled pore space) is largely in control of oxygen availability in the soil, although microbial activity can also play an important role through the consumption of oxygen and respiration of carbon dioxide (CO_2) (Sylvia, 2005). Factors influencing porosity are important for movement and exchange of soil water and thus emissions of gaseous N, which have been observed to correlate with water filled pore space in agricultural soils (Khalil and

Baggs, 2005; Verhoeven, 2017). Orchard soil on site ranged from 66% sand to 86% sand (Table 2.2), and sandy soil is known to have lower porosity than clay rich soil. This could partially explain Orchard 4 (86% sand) contributing the lowest cumulative N_2O fluxes two out of three seasons, as Callesen et al. (2007) found N pools in coarser textured soils are more variable and closely respond to climate factors (mean annual temperature and mean annual precipitation) (Callesen et al., 2007). Studies of soil texture's influence on N mineralization have been varied, showing clay content corelating inversely with N mineralization (McLauchlan, 2006) as well as having no influence on N pools and mineralization (Côté et al., 2000; McLauchlan, 2006). Higher sand content and lower porosity result in decreased water retention, thereby reducing the time during which the soil oxygen continuum favors the greatest N_2O production. Soil water content and temperature are both considered important to the processes controlling soil greenhouse gases production (Luo et al., 2013). Soil temperature can influence soil gas fluxes by increasing metabolic rates and facilitating weathering of soil aggregates which increases potential for substrate and oxygen accessibility. Our study found peak N_2O fluxes follow seasonal changes in the soil environment with the greatest N_2O fluxes in the orchards corresponding with soil temperatures of approximately 20-25 °C. Changes in capillary soil water (available water not bound tightly within the soil matrix) also influences soil gas emissions through multiple mechanisms, including regulating available oxygen and distributing substrates for metabolic pathways. Highest fluxes were recorded in mid-growing season (spring) when the fertigation schedule is in full swing, soil temperatures are consistently warmer and plant physiological metabolism is highly active.

Of particular importance to porosity are physical factors of bulk density and texture (Brady and Weil, 2010), which could provide correlating indicators for potential N_2O production in soil. In our study greater cumulative N_2O emissions occurred in Orchard 3 during the 2017 and 2018 seasons, which has less clay and more sand than Orchard 1. Orchard 4 has the lowest proportion of clay and produced least cumulative N_2O emissions for 2018 and 2019, and second lowest during 2017. Having the highest proportion of sand and lowest bulk density may have contributed to lower cumulative emissions in Orchard 4, given that sand allows more rapid mass flow of soil solution reducing residence time of available water and substrates. Other soil characteristics (i.e. temperature, substrate availability, pH) also play an important role in regulating soil N_2O processes (Zhu-Barker & Steenwerth, 2018). Temperature is considered a key driver of microbial activity in general, while availability of substrates such as NH_4^+, NO_3^- and soil carbon (C) may regulate microbial productivity. In our study, the majority of N_2O fluxes occurred below 90 mg of inorganic N per kg of soil, with peak fluxes occurring between 25-45 mg kg^{-1}. Upon inspection of the data, we did not see a direct correlation between greater concentrations of soil inorganic N and N_2O fluxes. Additionally, soils have unique critical pH values, below which N_2O production is significantly inhibited, and Wang et al. (2017) suggests that pH may be “the chief modifier for regional N_2O emissions” (Venterea & Rolston, 2000; Wang et al., 2018). The soils in this study are around neutral, ranging from pH 6.75 to 7.28, and above any potentially inhibiting low pH threshold conditions. The multitude of factors that may exert influence on soil N_2O production is matched by the variability of observed soil fluxes (Bouwman, 1996). Hence, soil N_2O production is widely variable spatially and temporally. Although the variability in fluxes is partially attributable to temperature and precipitation, it is also explained by heterogeneity of soil characteristics.

Soil Rewetting and Nitrogen

Physical distribution of irrigation water to the soil is a main driver of soil N_2O emissions in agricultural systems through its influence on soil water content and dispersal of essential substrates for nitrification and denitrification through the soil matrix (Smart et al, 2011). However, N_2O response across climates, soils, and fertilizer types is nonlinear with increasing N input rates (Shcherbak et al., 2014). Spatial patterns of soil wetting are determined by the irrigation emitters in perennial agriculture systems (Zhu-Barker & Steenwerth, 2018). In this study we see that fluxes were consistent across the chamber collar distances representing the wetted area from the emitters. We observed N_2O fluxes within three days of fertigation events were generally higher than other fluxes (Figure 2.5), indicating application of fertilizer and water played a role in these orchards. When irrigation is initiated and soil water content increases, O_2 diffusion decreases and N_2O production is promoted as soil conditions become anoxic (Zhu et al., 2013a). In Figure 2.12 we see a non-linear response of N_2O fluxes to soil water content in our study orchards, fluxes were greatest around 25% water content. Increasing soil water content above 25% in our study soil is likely associated with available O_2 becoming limited in the soil matrix, promoting the need for alternate electron acceptors. Heterotrophic bacteria utilize N compounds (NO_3^- and NO_2^-) as alternate electron acceptors when O_2 availability is limited, producing N_2O as an intermediate (Zhu-Barker & Steenwerth, 2018). Chemoautotrophic nitrifiers use ammonia as an energy source in the presence of O_2 through several pathways, collectively referred to as ammonia oxidation (Zhu et al., 2013). Nitrifiers likely drive the N_2O fluxes occurring on the lower end of soil water content values in Figure 2.12.

As irrigation water is distributed through the soil, N_2O production from heterotrophic denitrification and ammonia oxidation approaches optimum conditions, known to occur above 60% water fill pore space (WFPS), which corresponds to approximately 24%, 25%, and 26%

volumetric soil water content in Orchard 1, 3, and 4 respectively (Bateman & Baggs, 2005; Linn & Doran, 1984). The dominant pathway for soil N_2O production shifts as proportion of soil pores filled with water increases, and the majority of nitrifier derived N_2O emissions are assumed to occur at lower soil water contents while observations of denitrification pathways peak between 70%-90% WFPS, calculated as 24%-40% soil water content in our orchard soils (Dobbie et al., 1999; Venterea et al., 2010; Zhu-Barker & Steenwerth, 2018). Soils near saturation are limited in N_2O emissions, likely because compounds remain in solution and are further reduced to N_2 prior to atmospheric diffusion (Davidson, 1991; Dunfield et al., 1995). The influence of soil water content on N_2O production has been observed in California almond orchards by Schellenberg et al. (2012) who observed N_2O emissions generally peaked when water filled pore space exceeded 30% (approximately 12% soil water content in our Orchards soils) in California almond orchards, and in California vineyards, Yu et al. (2017) determined soil gravimetric water content was the main factor driving observed N_2O fluxes. In our study we see peaks in N_2O fluxes occur during spring, when soil water is available (20%-35% soil water content). Fertigation events during this time provide regular rewetting to the soil matrix, followed by dry down after the irrigation system is turned off. Fertigation provides both irrigation and fertilizer (N) simultaneously, providing the potential for soil N content to be highest when the soil is wet.

Application methods, rates, and types of N fertilizers all contribute to N_2O fluxes in perennial agriculture. Availability of substrates is a known control for soil N_2O production, and application rates of N fertilizers (substrates for N_2O) can impact annual emissions (Stehfest and Bouwman, 2006). We observed in our orchards that when inorganic N substrate concentrations were between 30-40 mg kg^{-1} soil, N_2O fluxes were highest, but they did not increase linearly with increasing inorganic N (Figure 2.13). Schellenberg et al. (2012) demonstrated soil N_2O

production in California almond orchards may be affected by the type of nitrogen input, with calcium ammonium nitrate fertilizer resulting in lower fluxes than urea ammonium nitrate, although no significant difference was observed. Similarly, Wolff et al. estimated N_2O fluxes from urea ammonium nitrate fertigation to be approximately double the emissions from soluble nitrate fertigation. Fertilizers applied during our study was a combination of ammonium nitrate compounds (calcium ammonium nitrate and urea ammonium nitrate) and soluble nitrate solutions, all of which contribute to inorganic N pools in the soil but upon visual inspection no correlation of the different fertilizers to N_2O fluxes was observed.

Abiotic processes and biotic enzymatic pathways of soil N_2O production are influenced by similar soil factors, including inorganic nitrogen pools (Butt and Lees, 1960; Zhu-Barker & Steenwerth, 2018). Substrate availability from the inorganic N pool functions as a control of many N_2O production pathways, particularly the rates of ammonification, denitrification, and nitrification (Burger and Jackson, 2003; Burger et al., 2005; Sánchez-Martín et al., 2008; Steenwerth and Belina, 2008a, 2008b). In California almond orchards, peak N_2O emissions were observed when soil inorganic pools exceeded 20-30 mg N kg $^{-1}$ soil (Schellenberg et al., 2012). Similar trends were observed in our orchards, with N2O fluxes being highest when inorganic N pools ranged from 30- 40 mg N kg^{-1} soil (Figure 2.13). Inorganic N pools were shown to directly relate to N_2O emissions in California vineyards, although frequently in association with other soil characteristics such as clay content and texture (Yu et al. 2018). Inorganic N (either applied as fertilizer or naturally occurring) can be used as a substrate for microbial metabolic pathways, some of which result in the production of gaseous N compounds and could provide a catalyst for C gas production. The majority of observed soil inorganic N in our orchards ranged between 0-

35 mg kg $^{-1}$ of soil, and the greatest N_2O emissions corresponded with approximately 30 – 55 mg kg $^{-1}$ of soil.

Grower and Modeling Applications

The results of this study provide specific examples of GHG emissions from orchard soils which have incorporated a novel fertigation strategy intended to meet the physiological crop demand for economic yields while minimizing losses of applied nutrients and associated impacts on the atmospheric and aquatic ecosystem (Khalsa et al., 2020b; Muhammad et al., 2009, 2015; Smart et al., 2011). By observing the response of these orchard soils to HFLC fertigation technique, we have gained a better understanding of the potential for fertigation strategies to provide growers with management decisions to control gaseous losses. The variability observed helps growers understand that orchard response will be unique from location to location. Examining cumulative greenhouse gas emissions allows us to understand the relative seasonal contribution of the gases to the atmosphere from each orchard.

The study is contributing to understanding agricultural GHG contributions in response to management decisions by providing input for the USDA Greenhouse gas Reduction through Agricultural Carbon Enhancement network (GRACEnet) research program. GRACEnet is focused on quantifying greenhouse gas emissions from cropped and grazed soils in order to develop improved management practices to reduce emissions and improve soil's role in promoting desirable GHG concentrations in the atmosphere (Del Grosso et al., 2013).

The collection of soil parameters and emission fluxes under documented orchard management scenarios can be used to further develop predictive biogeochemical models, which are key to informing policy and agriculture management decisions related to nutrient cycling and GHG production. Two specific models we have worked with which will likely utilize this data for parameterization are the DeNitrification DeComposition (DNDC) model and the Daily CENTURY (DayCent) model. These models, and other mathematical models like them, are powerful tools to simulate processes resulting in carbon and nitrogen transformation, loss and storage in soils (agricultural and wildlands) (Del Grosso et al., 2011; Gilhespy et al., 2014). Basic model inputs include soil characteristics, management practices, land use, and climate information, with a vast array of additional parameters that can be standardized from previously validated calibration data or specified if collected. The model outputs could be parameterized with the data collected from our study to develop more accurate simulations of biogeochemical process in California almond orchards and their soil response to potential changes in climate and management practices (Del Grosso et al., 2011; Gilhespy et al., 2014; Sulman et al., 2018).

Future Study

While this study provided some insight into the dynamics of N loss through soil N_2O production during the application of HF-LC fertigation on an almond orchard, it was limited in scope and design. If one considers the opportunity to develop another project to address the objectives of this study with fewer limitations, a different approach for site selection would be paramount. In order to appropriately address the potential impact of heterogenous soil conditions, it would be pertinent for the study to include orchard locations throughout the range of soil landscapes present in the Central Valley growing region of California. This should include orchards on the alluvial fans along the lower valley regions, plantings on well-developed low terraces of granitic alluvium, as well as orchards further from the valley center along the undulating high terraces of metamorphic rock alluvium. Soil characteristics would be utilized to identify distinct soil types within these landscapes, focusing on variation in soil chemical, physical, and mineralogical indices. Ideally, at least three orchards representing each soil type and growing landscape would be chosen for study. This variety of soil types would allow more rigorous testing of hypothesis related to variable soil conditions impacting N_2O production, such as physical characteristics (bulk density, texture, etc.) and chemical characteristics (pH, soil carbon content, etc.).

Adjusting the experimental design of the study locations would help develop well supported conclusions from the results. In order to test the ability of HFLC fertigation programs to control N_2O production, and how soil physical and chemical characteristics interact with and influence that control, a robust sample size of treatment versus control blocks should be included in the study design. Experimental design could follow a randomized complete block design, with each orchard having both HF-LC (treatment) and standard grower practices (control) simultaneously. The randomly assigned experimental blocks would be developed with three sampling locations within the treatment area and three sampling locations within the control area. Gas sampling at the locations could be improved by utilizing more advanced technology, including chambers designed for automated flux measurements such as those described by Grace et al. (2020) with at least four sampling time points to incorporate current flux estimate methodology. Soil sampling could also be expanded to include dissolved organic carbon and nitrogen to supplement the inorganic nitrogen measurements taken during each sampling campaign. In addition to initial soil characterization, it would be beneficial to track the C and N pools, soil pH, electrical conductivity, bulk density, infiltration, and aggregate stability, such that the potential impacts of these soil physicochemical characteristics on the seasonal N_2O fluxes could be evaluated thoroughly.

The impact of climate and orchard floor management on N_2O emissions creates interactions of unknown magnitude unique to each flux event, impacting interpretation of the measured results. Enhanced monitoring capabilities and homogenized site management to the greatest extent feasible, would greatly improve the ability to identify potential variations in N_2O fluxes attributable to non-treatment factors. Ideally, each orchard would include metrological sensors to continuously monitor microclimate characteristics in order to accurately model the soil gas flux relative to local climatic variables. These instrument locations could also continuously log irrigation and fertigation flow through irrigation lines, as well as soil temperature and water content. Orchard floor and tree management could be closely monitored or aligned, focus on replicates within trees of similar age and spacing, with irrigation distribution via similar emitter spacing, emitter brand, and pump control.

This updated and expanded project design would allow researchers to more accurately model the observed fluxes through statistical methodology. Included in this would be a mixed model approach to repeated measures analysis of variance in order to identify potential explanations for the majority of the variation observed. Additionally, the contribution of location specific factors on the fluxes, as determined by the mixed modeling, could be elucidated using path analysis approach. A research project designed and analyzed as described would provide strong evidence to support any conclusions made regarding the impact of orchard location heterogeneity on the efficacy of HF-LC as an appropriate best management practice to reduce N_2O production from California's Central Valley almond orchards.

Tables and Figures

(See Below)

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Tables and Figures

Table 2.1. Onsite soil series and taxonomic classification[1].

Soil Series	Taxonomic classification
Oakdale	*Coarse-loamy, mixed, active, thermic Mollic Haploxeralfs*
Modesto	*Fine-loamy, mixed, active, thermic Mollic Haploxeralfs*
Dinuba	*Coarse-loamy, mixed, active, thermic Typic Haploxeralfs*

[1]Soil Survey Staff, NRCS, accessed 2019.

Table 2.2. Orchard soil properties

Orchard ID	Soil Textural Composition			Texture Class[2]	pH (1:1) [1]	EC (1:1) [1]	Total N (%)[1]	Total Carbon (%)[1]	Bulk Density (g cm^3)
	Sand (%)	Silt (%)	Clay (%)						
Orchard 1	65.9	23.3	10.8	Sandy Loam	6.75	0.332	0.09	0.84	1.59
Orchard 3	78.4	16.6	5.0	Loamy Sand	7.28	0.095	0.06	0.67	1.53
Orchard 4	86.2	10.5	3.3	Loamy Sand	6.79	0.100	0.05	0.57	1.45

[1] Single sampling event snapshot of soil
[2] USDA NRCS Soil Survey Texture Class

Table 2.3. Orchard spacing

Orchard ID	Irrigation ID	Emitter Type	Tree Spacing (m)	Irrigation Spacing (m)
Orchard 1	FJ	Fan Jet	5.79	5.79
Orchard 3	FJ-2J	Fan Jet	7.01	3.52
Orchard 4	FJ-BL	Fan Jet, buried line	4.57	4.57

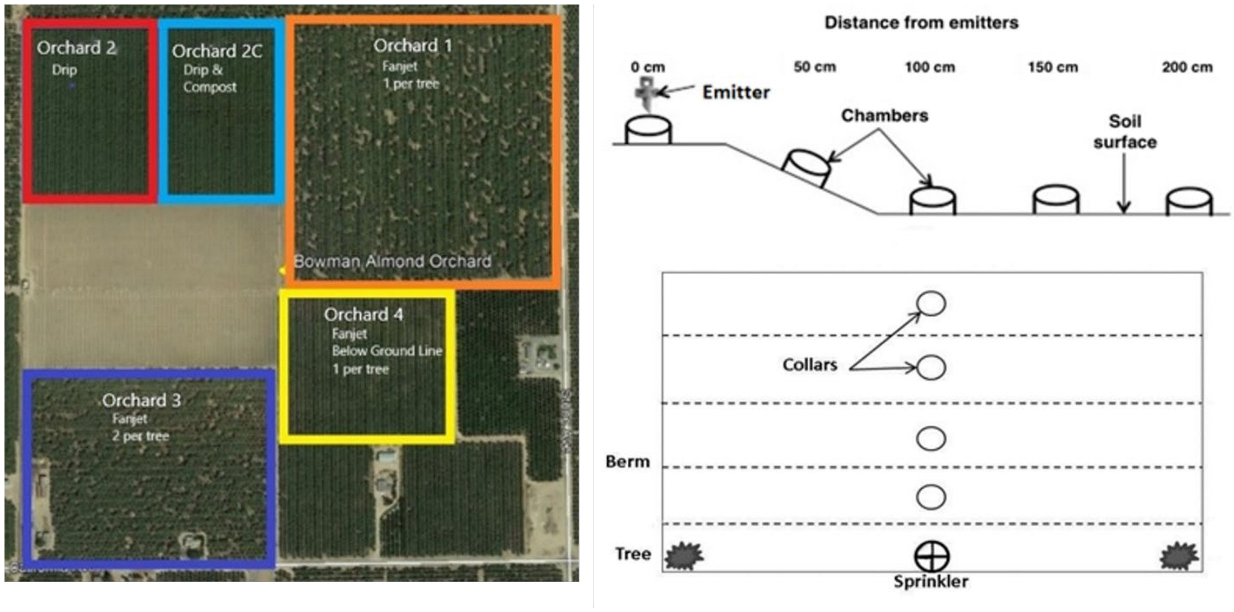

Figure 2.1: Orchards (experimental units) and chamber collar transect set up.

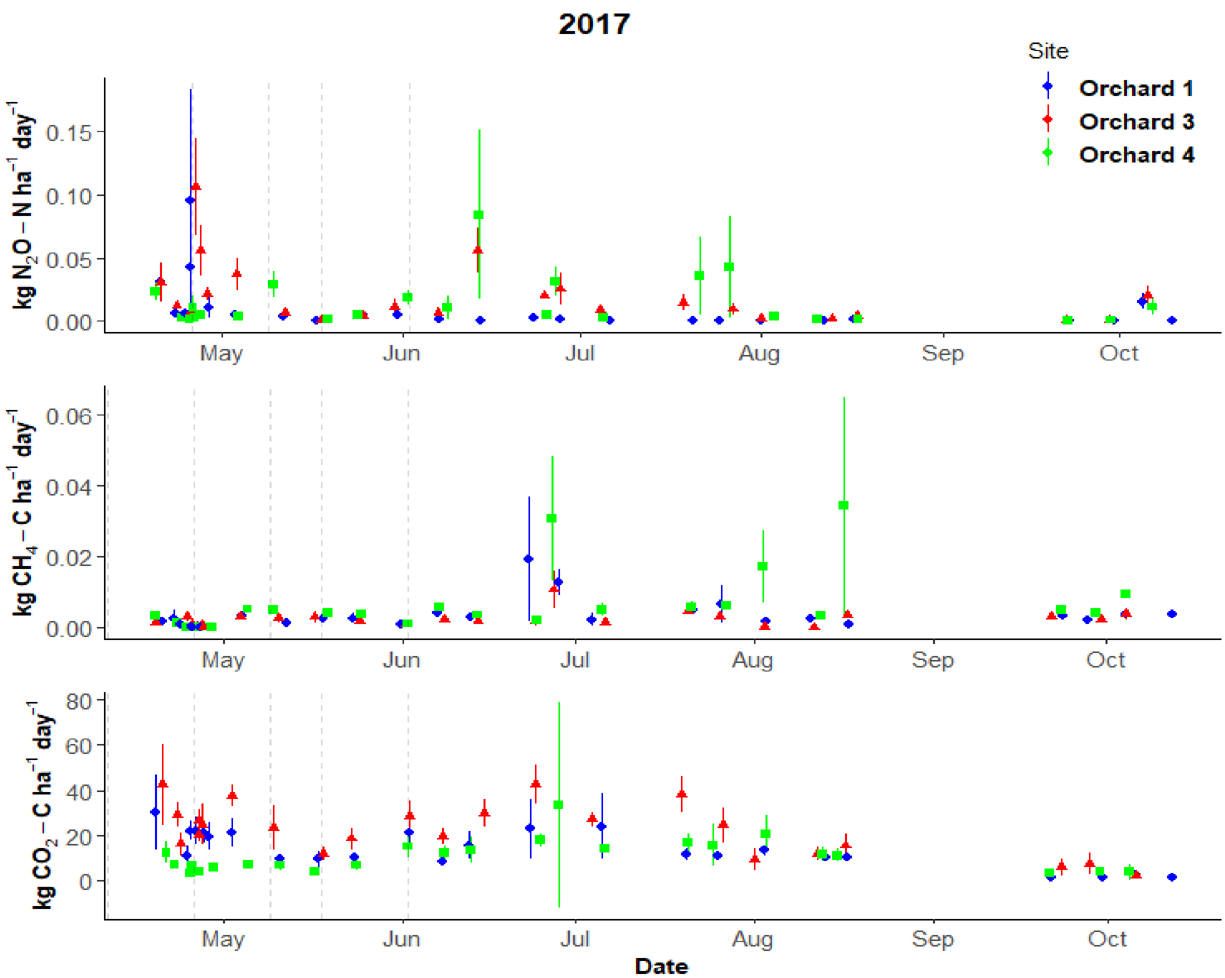

Figure 2.2: Gas fluxes on sampling days during the 2017 season of N_2O (top), CH_4 (middle) and CO_2 (bottom), orchard daily means (n=3) and standard errors are represented by different shapes and colors, dashed lines show dates of fertilizer events.

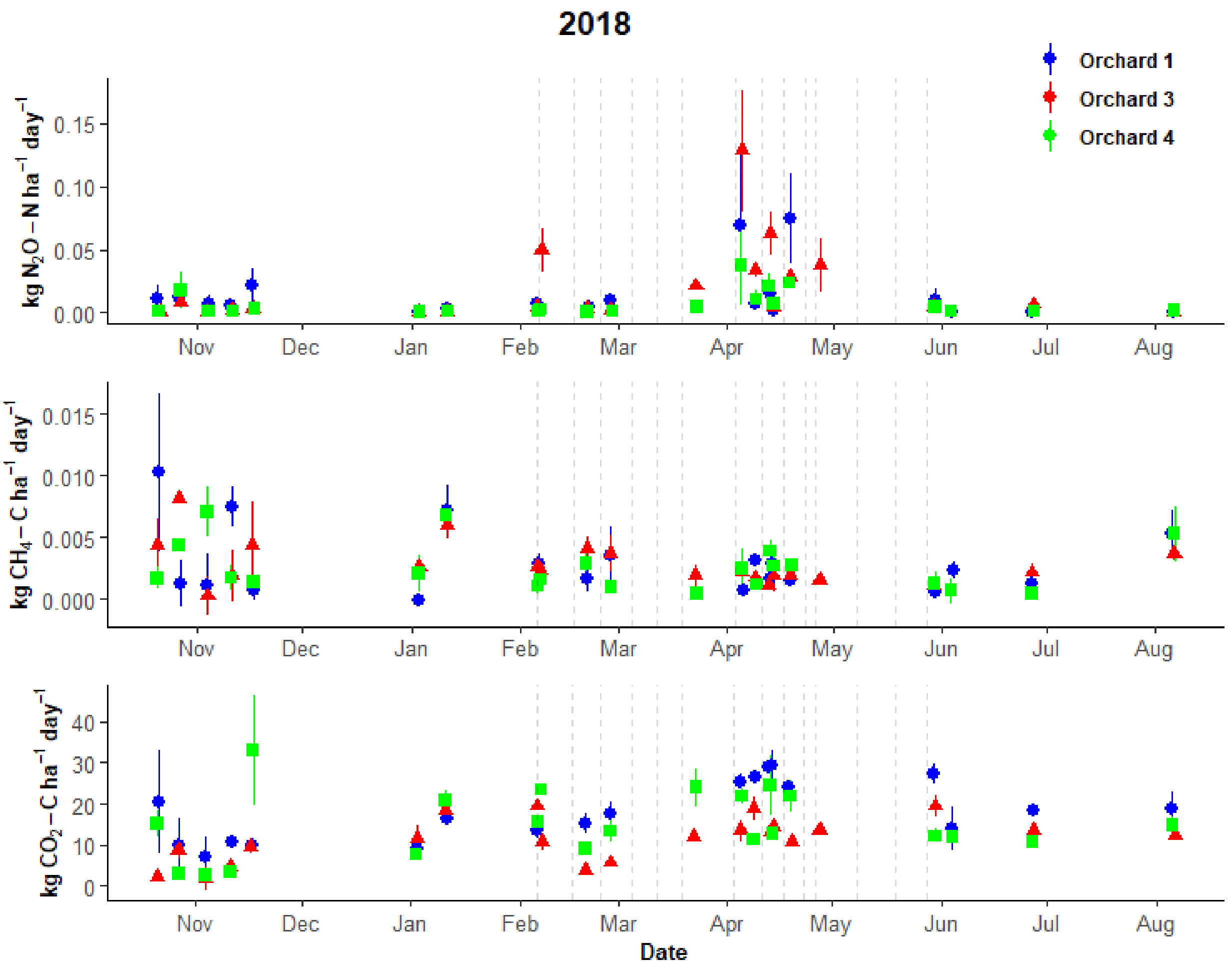

Figure 2.3: Gas fluxes on sampling days during the 2018 season of N_2O (top), CH_4 (middle) and CO_2 (bottom), orchard daily means (n=3) and standard errors are represented by different shapes and colors, dashed lines show dates of fertilizer events.

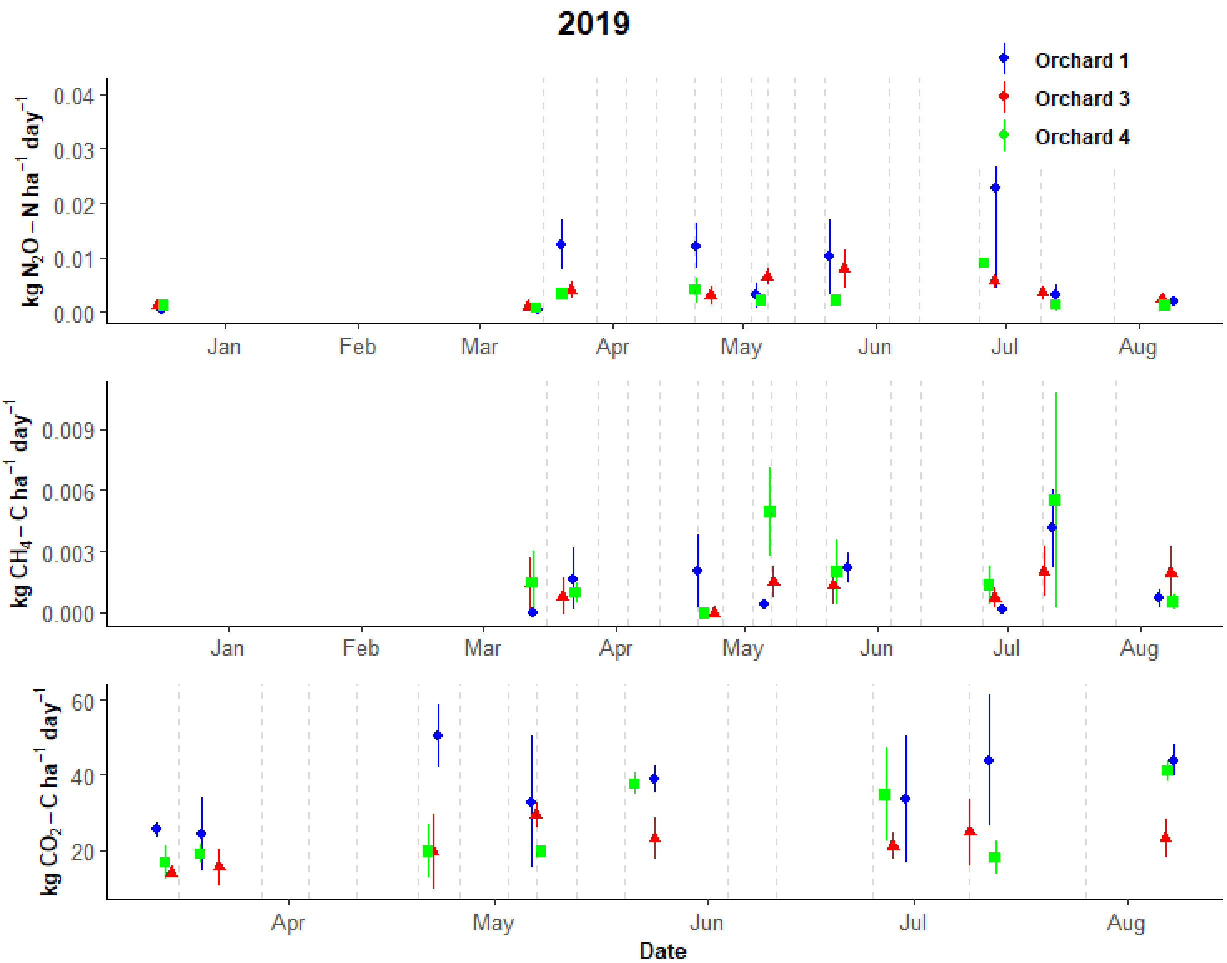

Figure 2.4: Gas fluxes on sampling days during the 2019 season of N_2O (top), CH_4 (middle) and CO_2 (bottom), orchard daily means (n=3) and standard errors are represented by different shapes and colors, dashed lines show dates of fertilizer events.

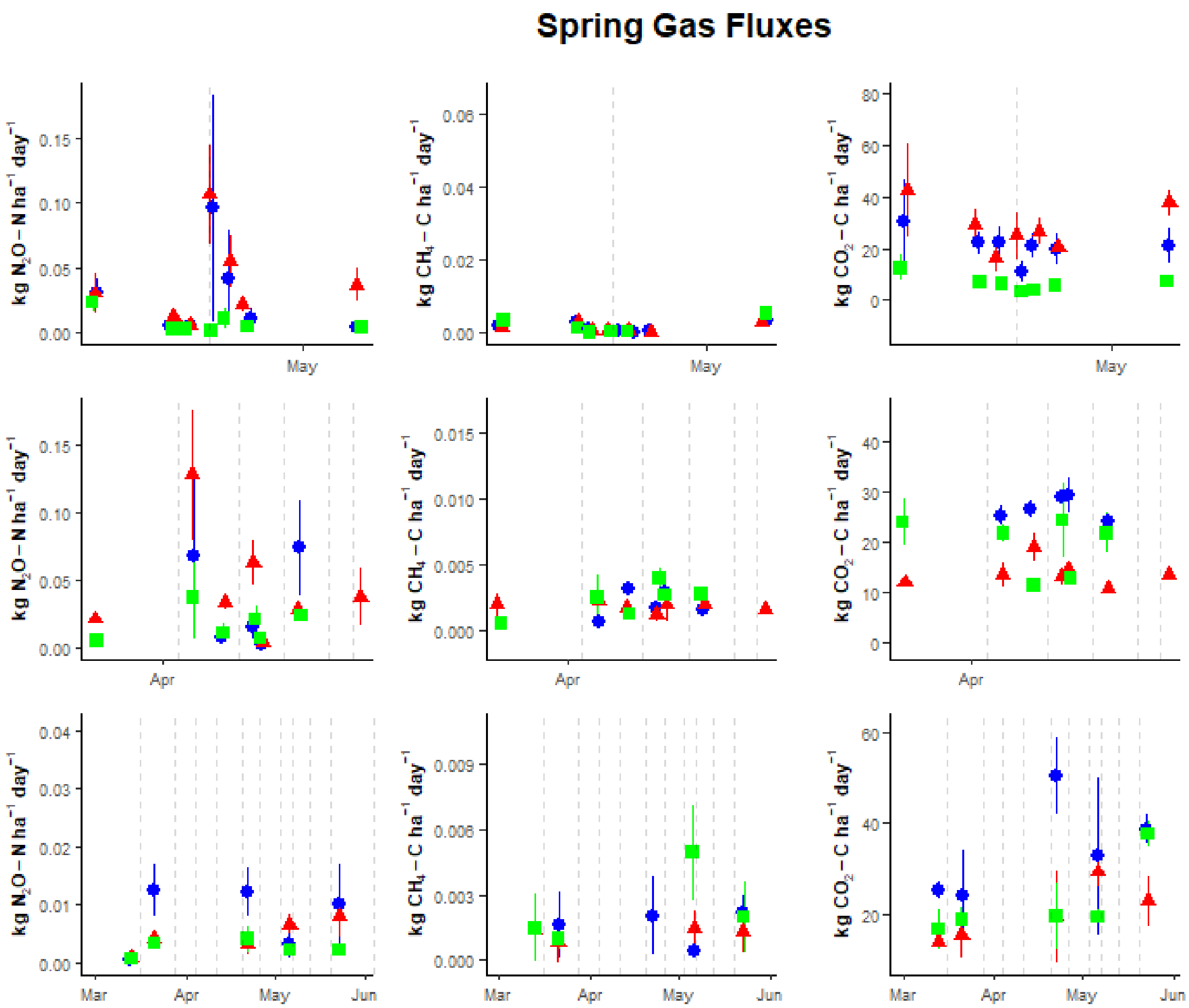

Figure 2.5: Spring N_2O, CH_4, and CO_2 fluxes for 2017 (top row), 2018 (middle row), and 2019 (bottom row). Orchard daily means (n=3) and standard errors are represented by different shapes and colors, dashed lines show dates of fertilizer events.

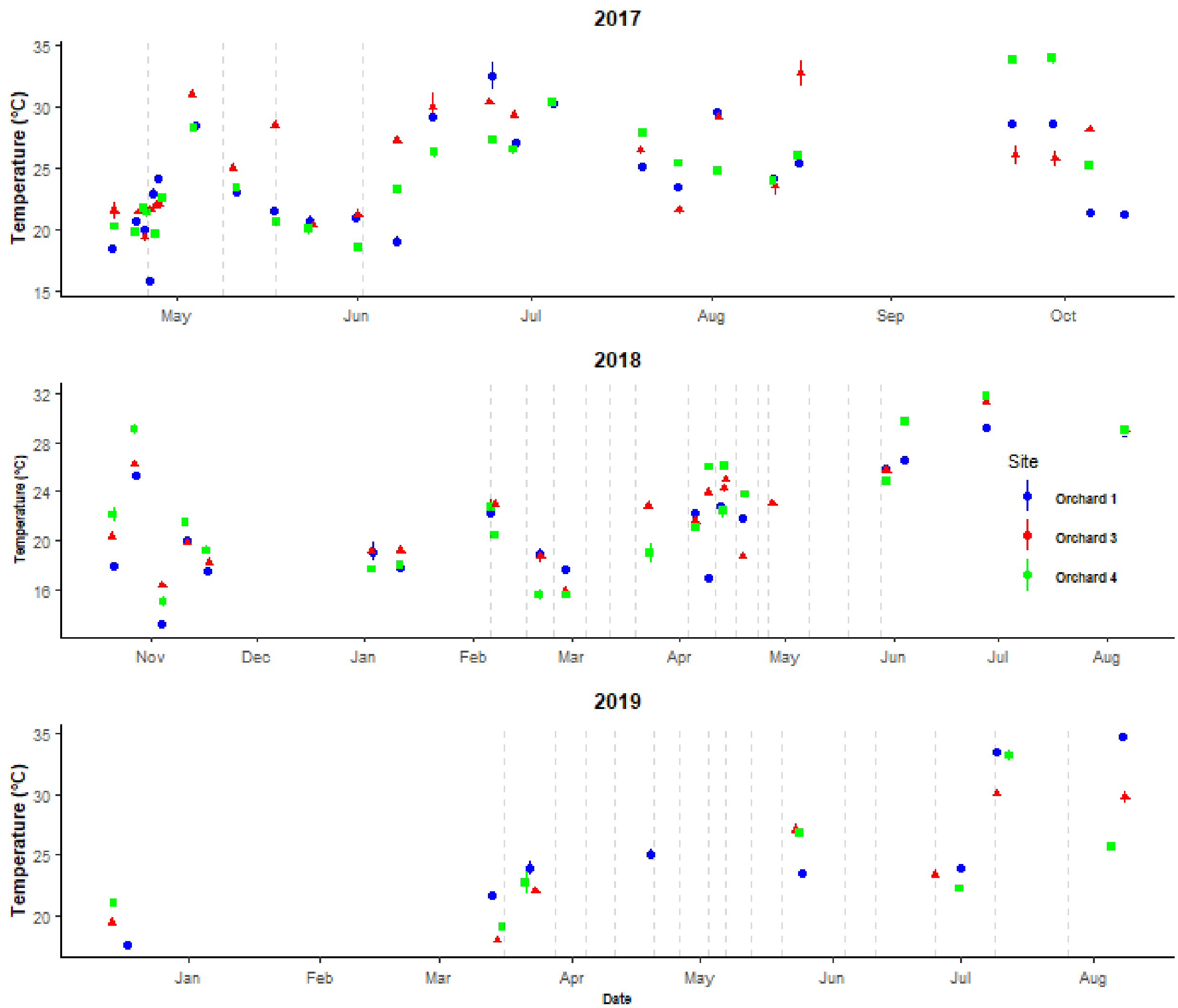

Figure 2.6: Mean temperature (°C) of soil during sampling events. Daily means during sampling (n=3) and standard errors for each orchard are represented by different shapes and colors.

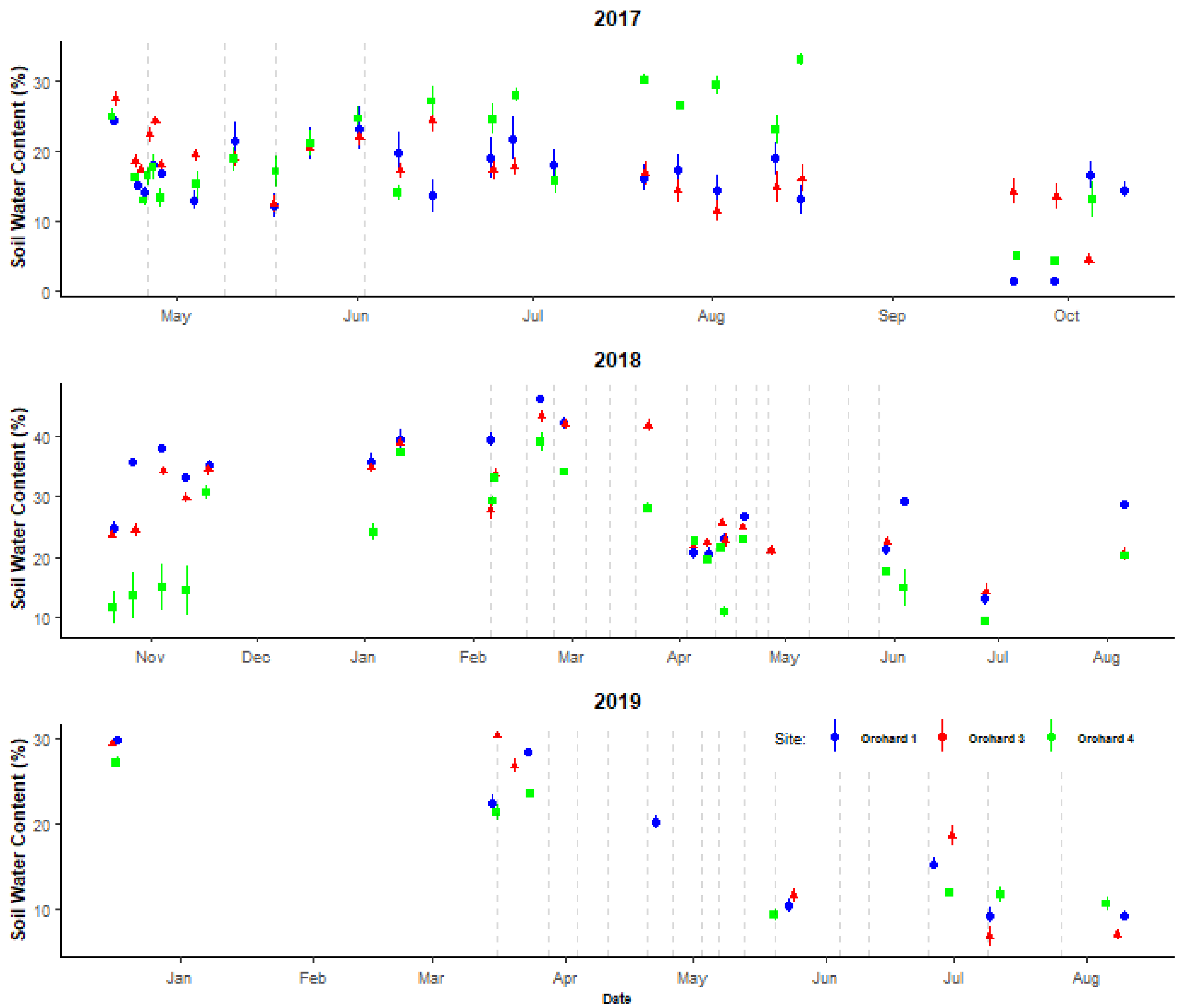

Figure 2.7: Mean volumetric soil water content (%) during sampling events. Daily means during sampling (n=45) and standard errors for each orchard are represented by different shapes and colors.

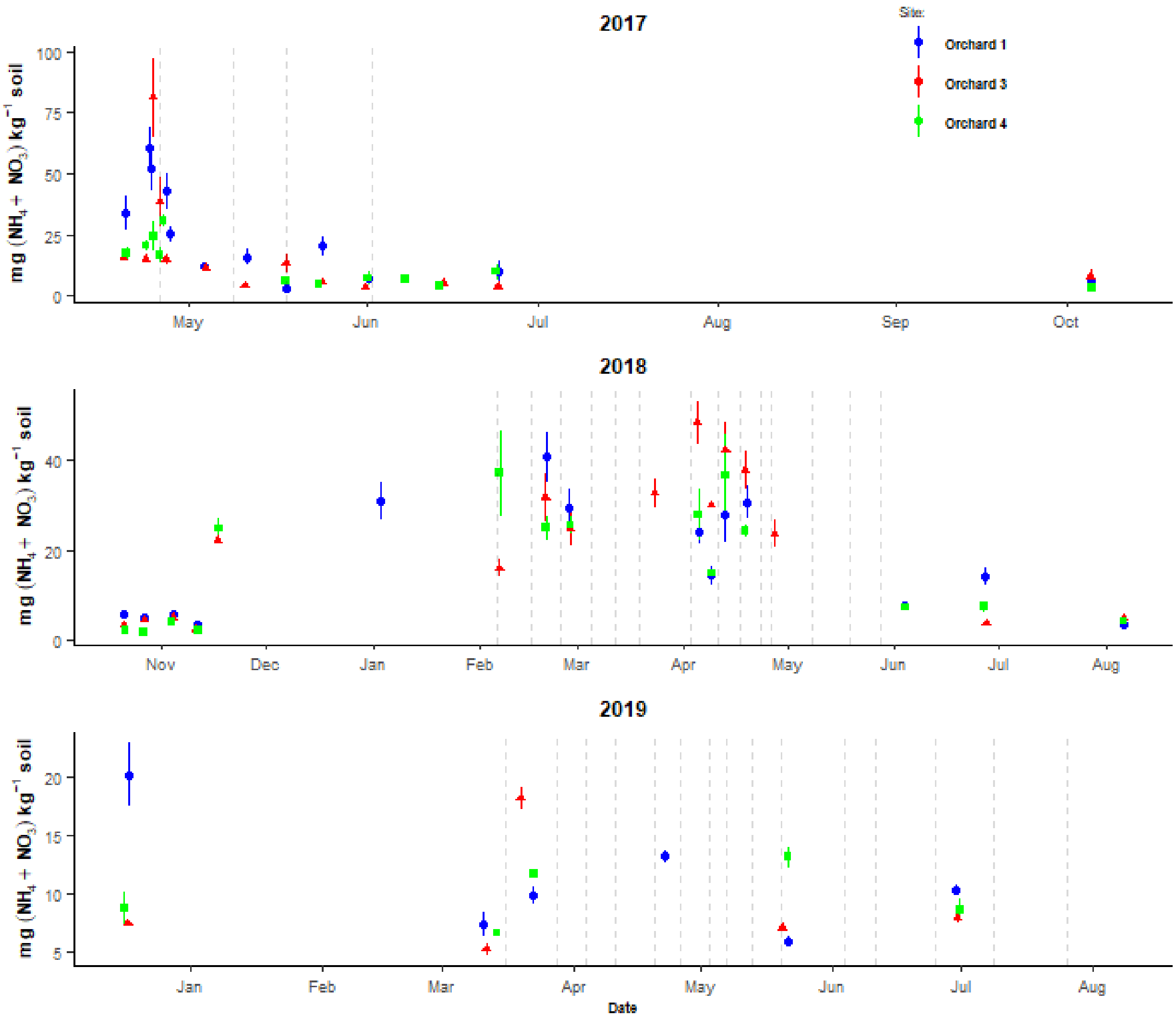

Figure 2.8: Soil inorganic N (mg $(NH_4 + NO_3)$ kg^{-1} soil) collected during sampling days each season. Daily means during sampling (n=5) and standard errors for each orchard are represented by different shapes and colors.

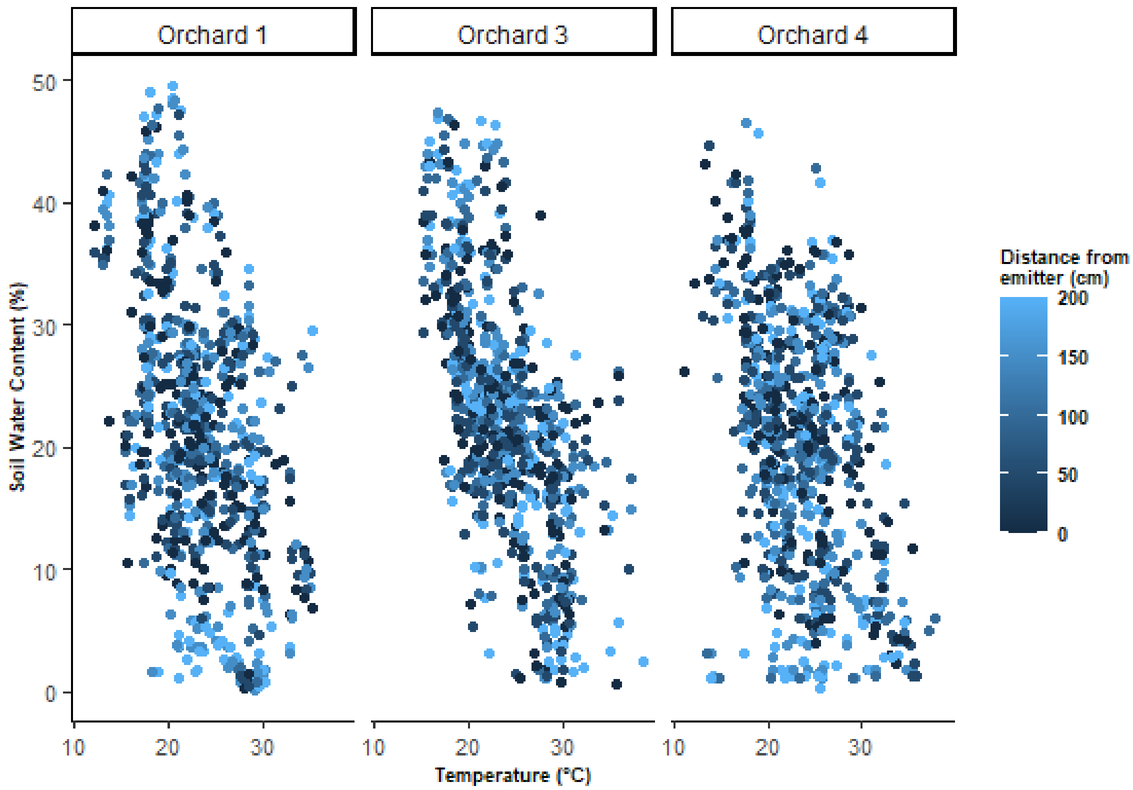

Figure 2.9: Measured volumetric soil water content (%) and temperature (℃) from all sampling days (3 seasons) in each orchard. Distance from the fan jet micro-sprinkler emitter at which the sample was collected is represented by shades of blue.

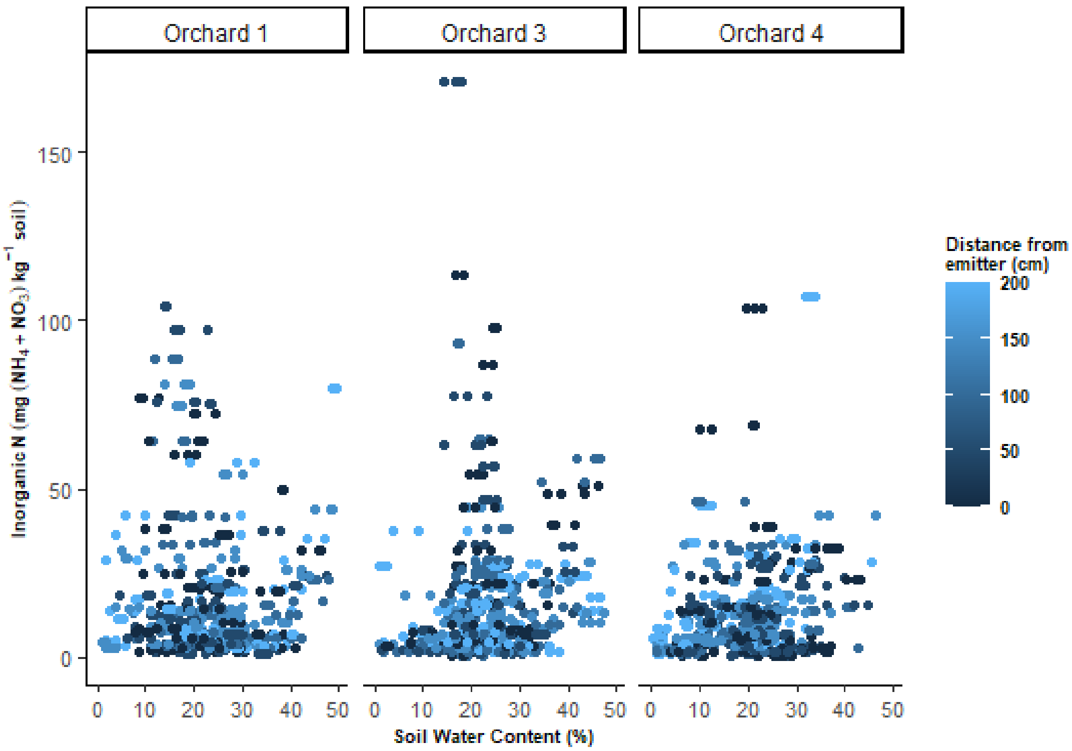

Figure 2.10: Soil inorganic N (mg (NH_4 + NO_3) kg^{-1} soil) and measured volumetric soil water content (%) collected during all sampling days. Distance from the fan jet micro-sprinkler emitter at which the sample was collected is represented by shades of blue.

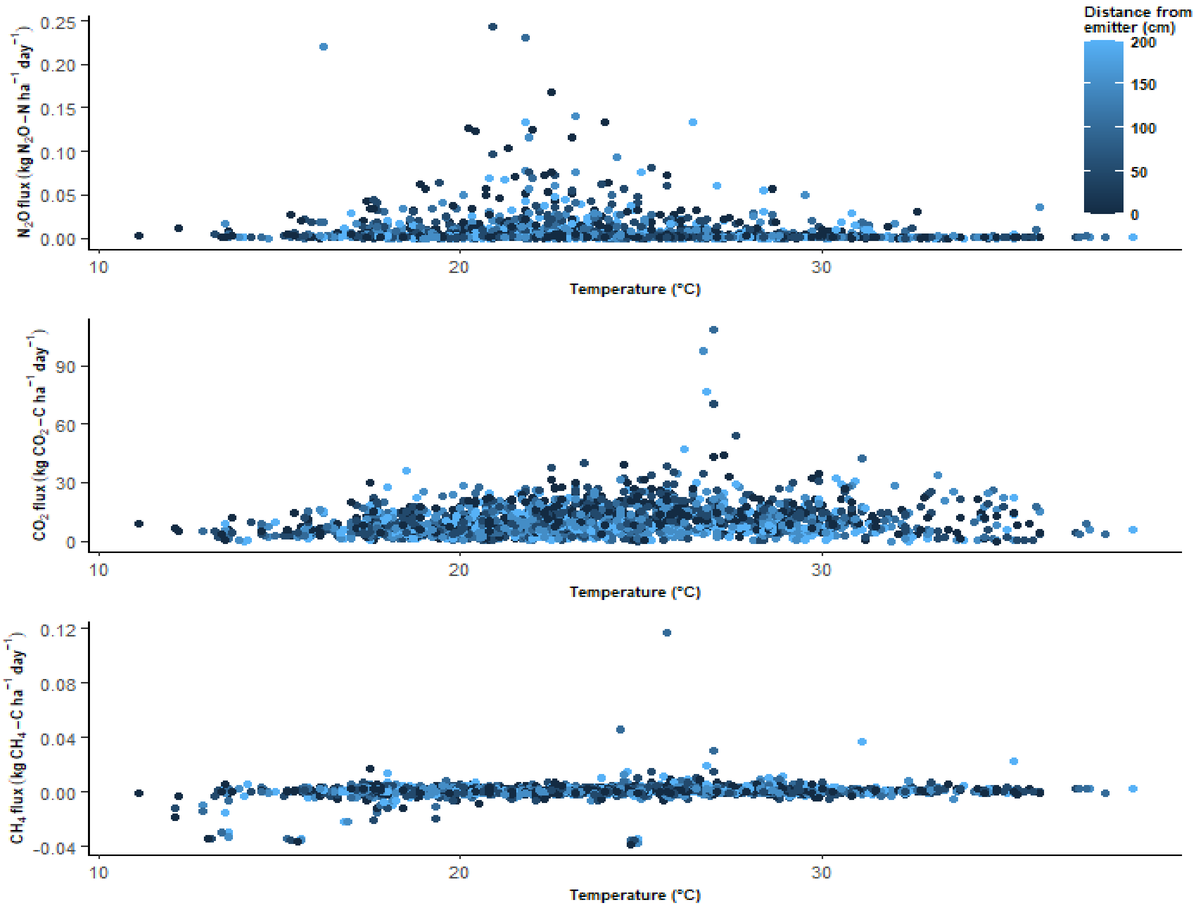

Figure 2.11: Gas fluxes (top: N_2O, middle: CO_2, bottom: CH_4) from all sampling collars relative to measured soil temperature (°C). Distance from the fan jet micro-sprinkler emitter at which fluxes were collected is represented by shades of blue.

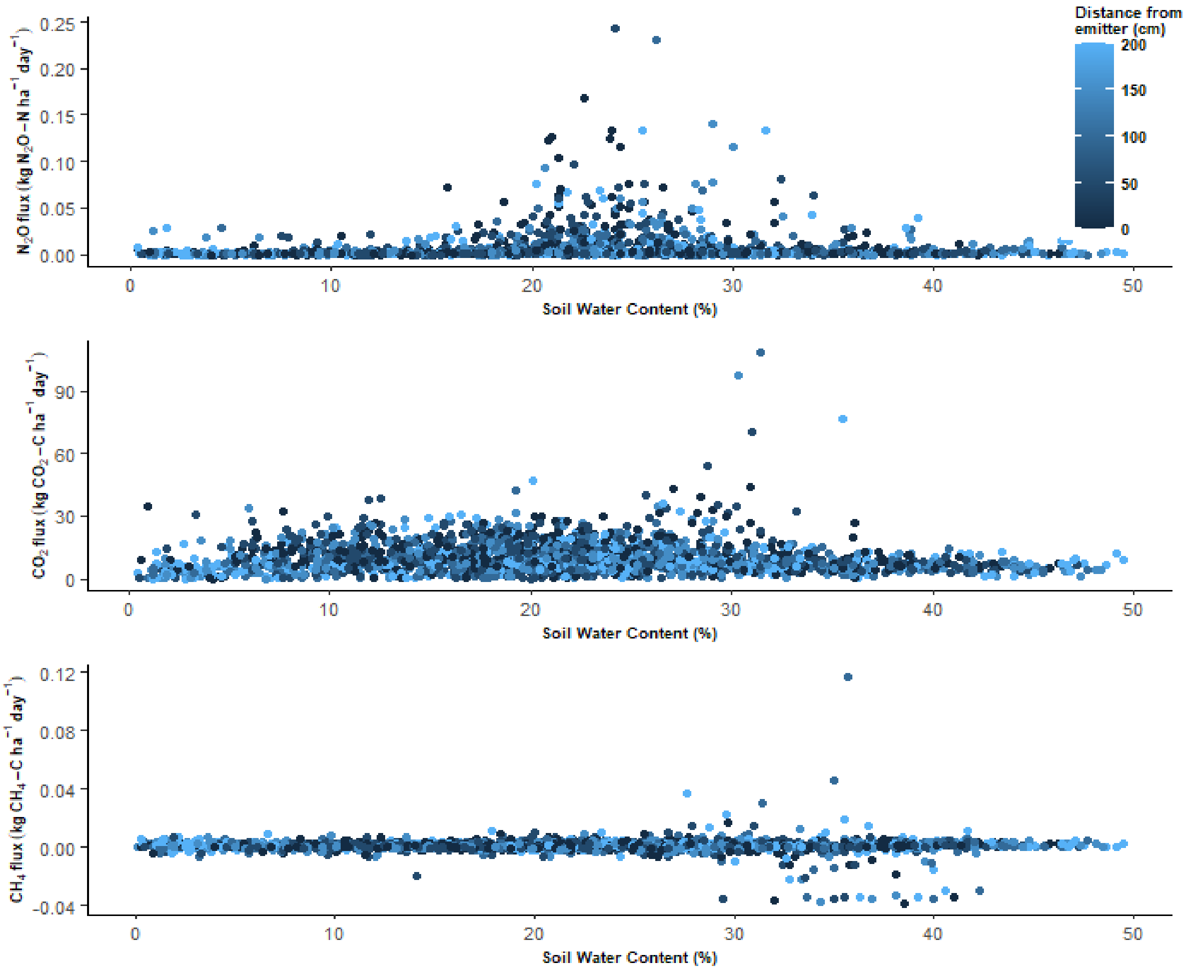

Figure 2.12: Gas fluxes (top: N_2O, middle: CO_2, bottom: CH_4) from all sampling collars relative to volumetric soil water content (%). Distance from the fan jet micro-sprinkler emitter at which the samples were collected is represented by shades of blue.

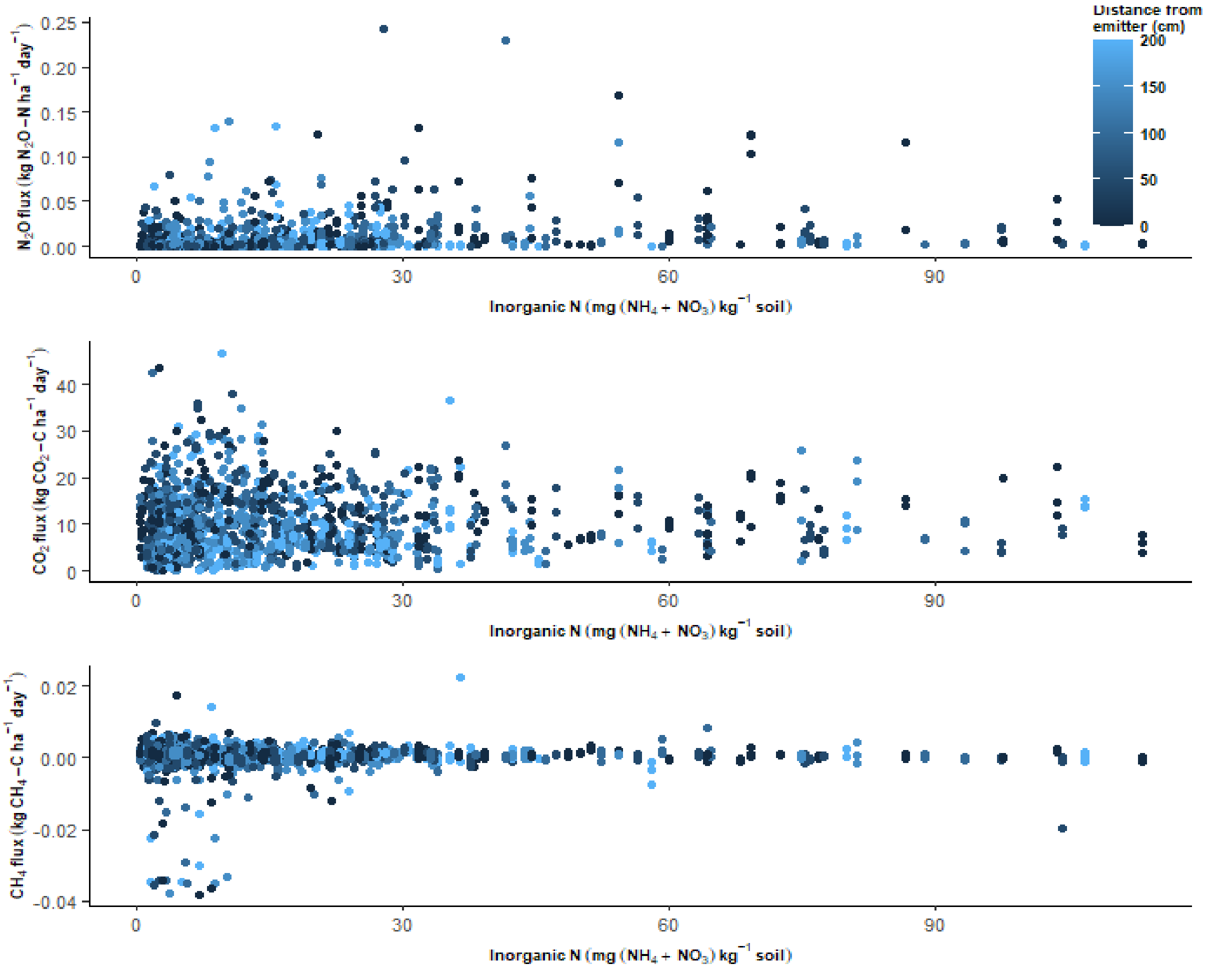

Figure 2.13: Gas fluxes (top: N_2O, middle: CO_2, bottom: CH_4) from all sampling collars relative to soil inorganic N concentrations. Distance from the fan jet micro-sprinkler emitter at which the samples were collected is represented by shades of blue.

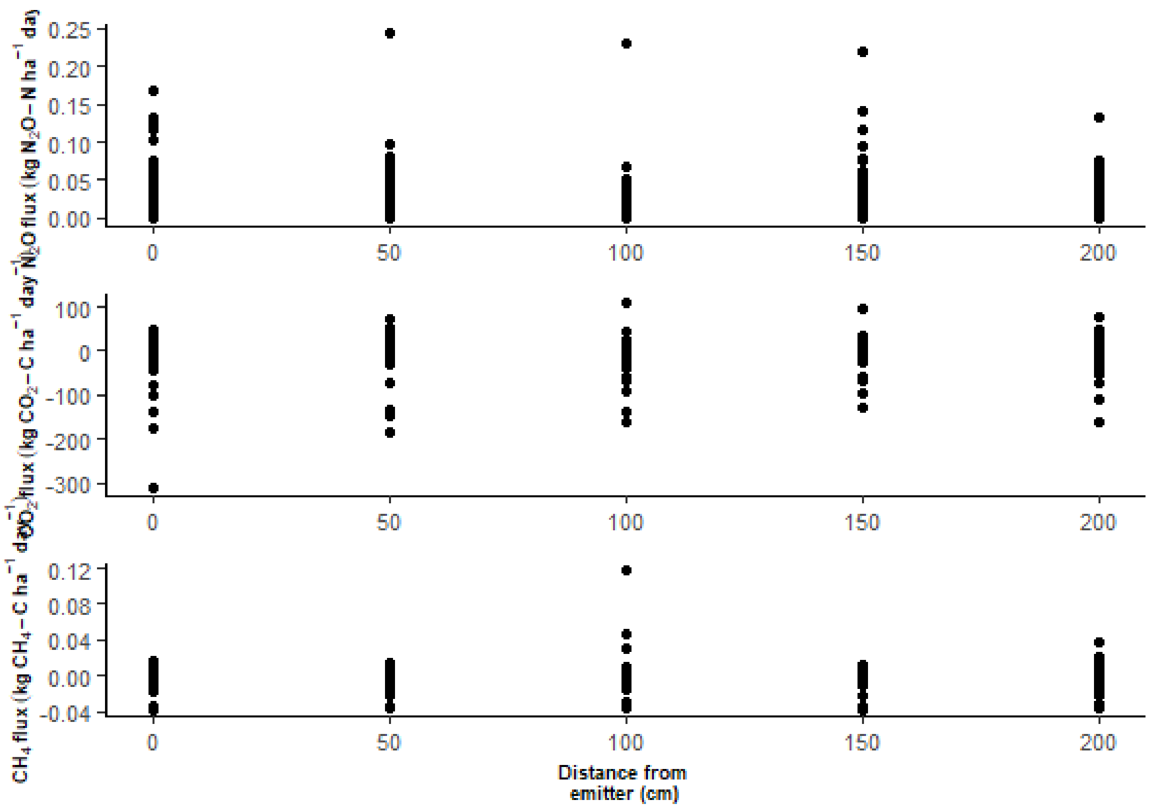

Figure 2.14: Gas fluxes (top: N_2O, middle: CO_2, bottom: CH_4) from all sampling collars relative to the distance (cm) the collar was placed from the fan jet micro-sprinkler emitter.

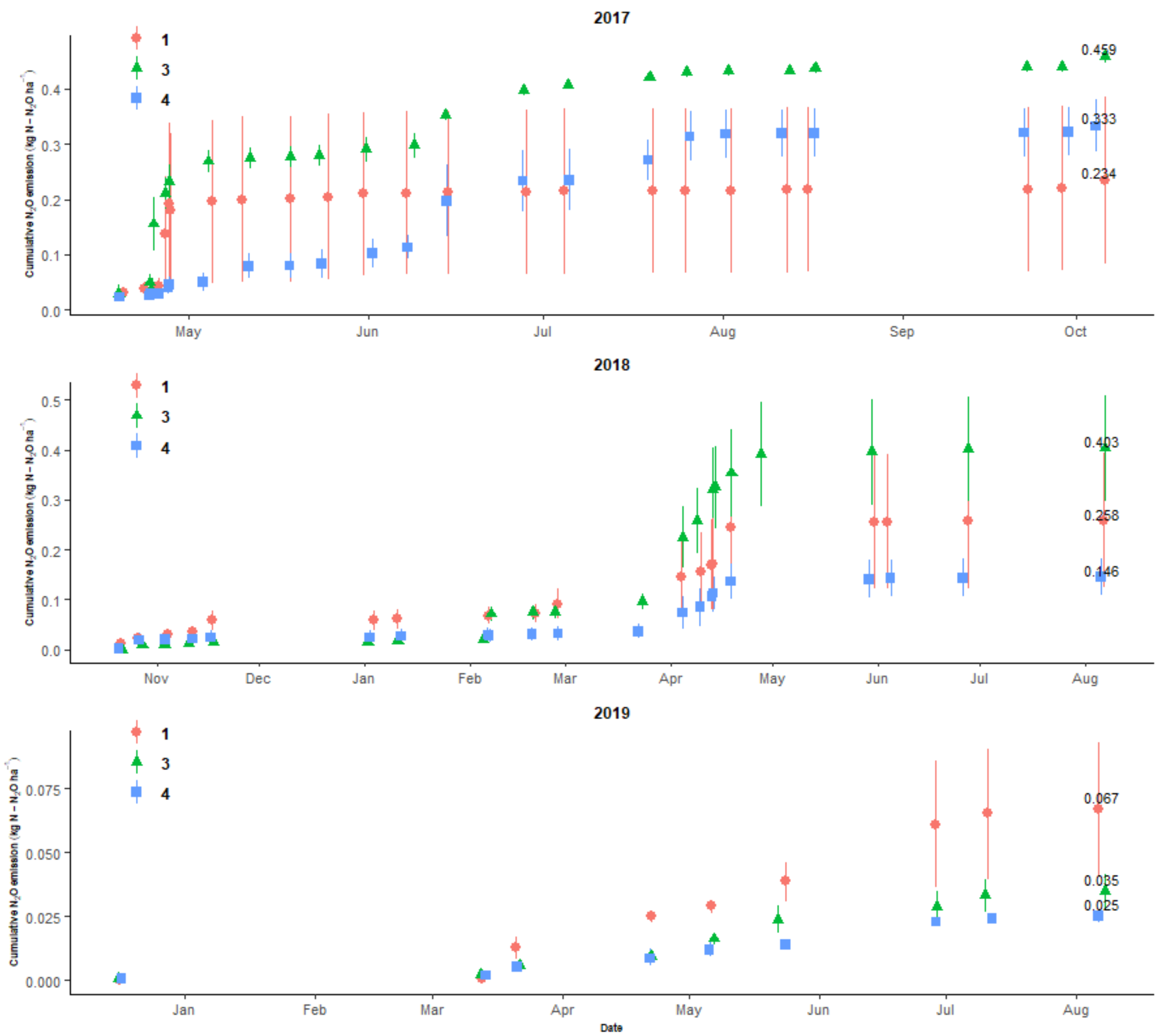

Figure 2.15: Cumulative N_2O emissions from each season. Mean cumulative emissions and standard errors (n=3) from each orchard are represented by different colors.

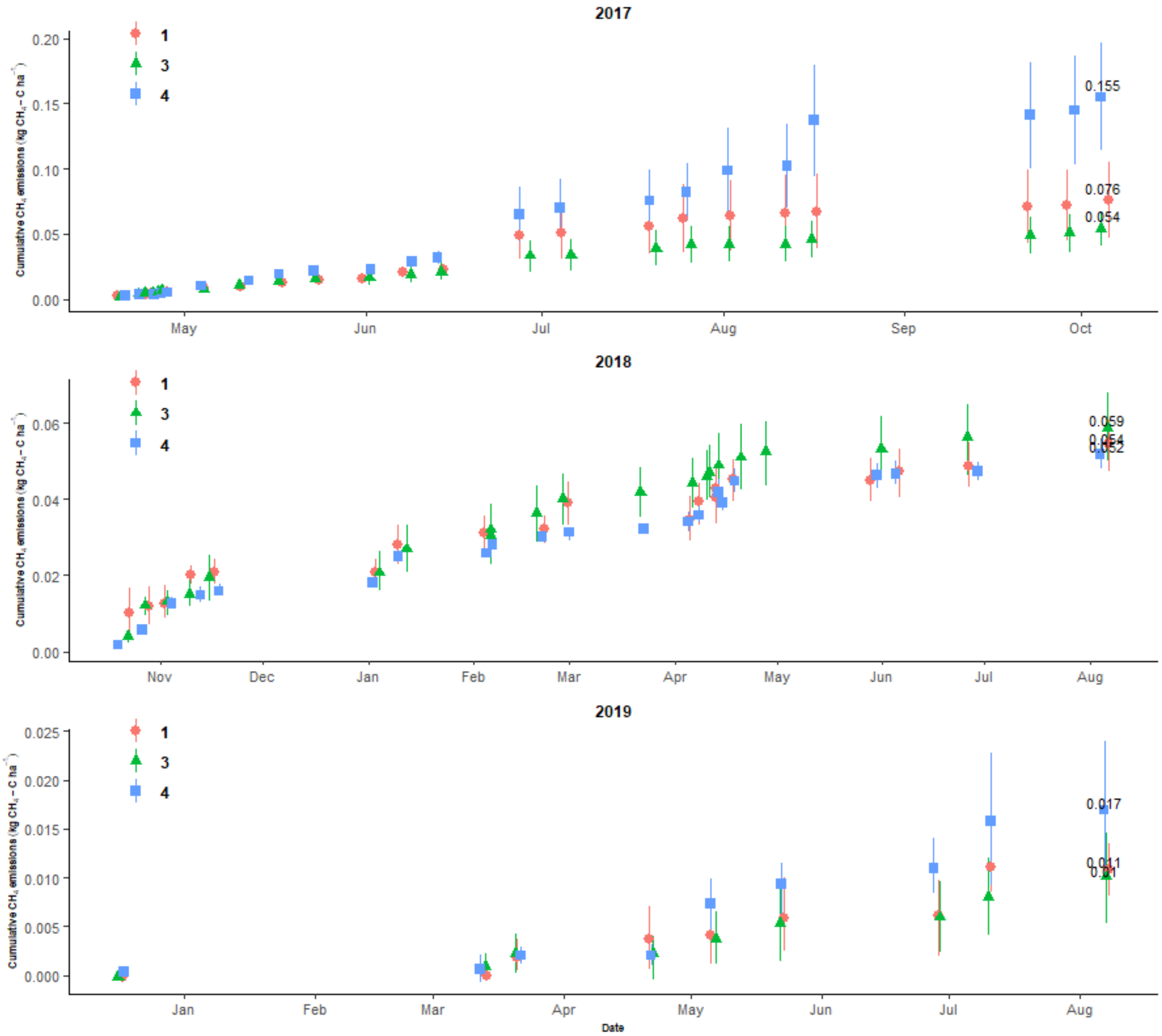

Figure 2.16: Cumulative CH4 emissions from each season. Mean cumulative emissions and standard errors (n=3) from each orchard are represented by different colors.

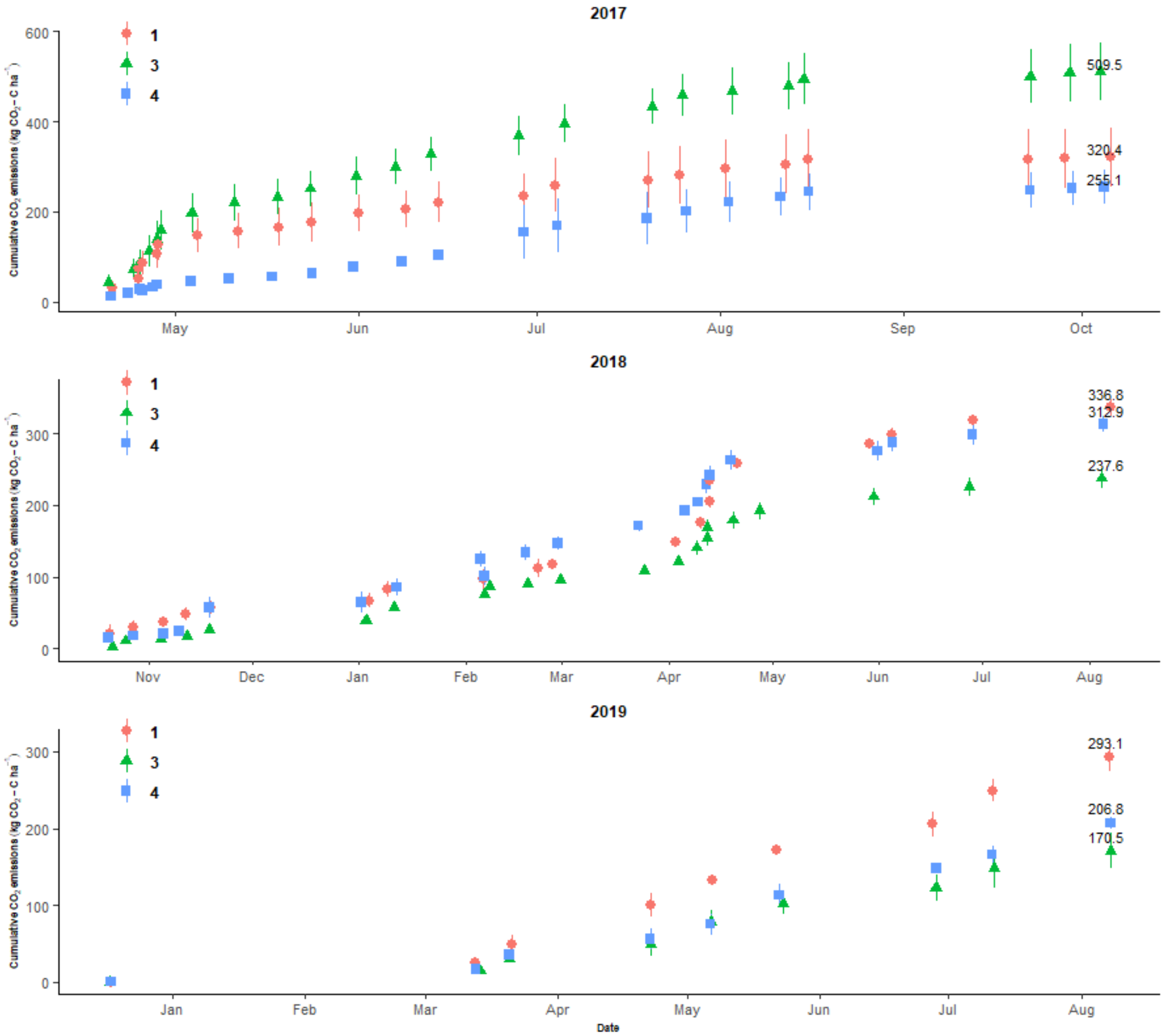

Figure 2.17: Cumulative CO_2 emissions from each season. Mean cumulative emissions and standard errors (n=3) from each orchard are represented by different colors.

Dissertation Chapter 3

Title: Long-term compost use and high frequency-low concentration (HF-LC) fertigation reduce N_2O emissions from a California almond orchard

Patrick K. Nichols[1]*, Dave Smart[2†], Majdi Abu-Najm[1], Patrick Brown[3], Thomas Harter[1], Kerri L. Steenwerth[4]*

[1] Department of Land, Air and Water Resources. University of California, Davis, CA 95616

[2] Department of Viticulture and Enology. University of California, Davis, CA 95616

[3] Department of Plant Sciences. University of California, Davis, CA 95616

[4] USDA-ARS, Crops Pathology and Genetics Research Unit, Davis, CA 95616

[†] Post-humous authorship

*Co-corresponding authors:

Patrick K. Nichols, pknichols@ucdavis.edu

Kerri L. Steenwerth, kerri.steenwerth@usda.gov

Abstract

Compost's use as an agricultural amendment offers an opportunity to reduce organic waste, as mandated in the State of California (USA) (SB 1383). Organic soil amendments, such as compost, can improve soil physical characteristics, nutrient cycling and soil carbon through the increase in soil organic matter. Fertilizer application through micro irrigation systems (i.e. fertigation) is increasingly common in almonds in California's Central Valley, as it is an effective method to manage water availability and nutrient loss. We examined the effect of compost application (7-year duration) on soil nitrous oxide emissions, inorganic N pools, soil temperature and water content, soil bulk density, and total C and N content. The almond orchard (Nonpareil cultivars interplanted with Aldrich and Carmel cultivars, all grafted on 'Nemaguard' peach rootstock [Prunus *persica* (L.) Bratsch]) was on an Oakdale sandy loam soil type. It was fertigated 14 times with urea ammonium nitrate or calcium ammonium nitrate, using high frequency and low concentration (HF-LC) applications, for a total of 195 kg N ha^{-1}. Soil without added compost ('no compost') tended to have higher fluxes (up to 2.75-fold) than soil with compost ('compost'). Emissions from 'no-compost' ranged from 0.29 to 5.5 g N_2O-N ha^{-1} day^{-1} while 'compost' ranged from 0.34 to 3.7 g N_2O-N ha^{-1} day^{-1}. Additionally, we observed a substantial reduction in annual cumulative N_2O emissions from 'compost', 11.5 g N-N_20 ha^{-1} compared to 20.1 g N-N_20 ha^{-1} in 'no compost'. Soil pH, EC, total C and N tended to be greater in 'compost', and bulk density tended to lower in 'compost' than 'no-compost'. No relationships between N_2O emissions and soil temperature, volumetric water content, water-filled pore space, and inorganic N pools were observed in either treatment. Our findings indicate that long-term applications of compost in perennial crops, in combination with a HF-LC nutrient management program, could reduce losses of N as N_2O to the atmosphere.

Keywords: Compost, almonds, nitrous oxide, floor management, organic soil amendments, greenhouse gas, high frequency low concentration, fertigation, nitrogen, drip irrigation.

Introduction

In agriculture, compost use is an ancient method for recycling waste and returning residues to the cropping system (Martínez-Blanco et al., 2013). Application of compost, the product of accelerated aerobic decomposition of organic waste under controlled conditions, increases soil organic matter (SOM), thereby improving aggregation, permeability, and net primary productivity of amended soil (Angin et al., 2013; Diacono & Montemurro, 2010; Ryals & Silver, 2013; Sodhi et al., 2009). The influence of long-term compost application on soil nitrogen (N) and carbon (C) cycling is not fully understood, particularly in woody perennial cropping systems like orchards.

Carbon dioxide (CO_2) and nitrous oxide (N_2O), two greenhouse gasses emitted during compost decomposition, impact global climate. Atmospheric CO_2 is influenced by oceanic, geological, and biotic carbon pools (Triberti et al., 2008). Soil contains fractions of C in multiple pools which are intricately connected to atmospheric C (Post et al., 1982). Increasing organic matter (OM) amendments to build the less labile fraction in soil and increase SOC residence times has been a proposed component of climate smart agriculture to maintain and enhance productivity and resilience of agricultural ecosystem functions (Bai et al., 2019; Steenwerth et al. 2014; Paustian et al., 1997). The potential of agricultural C pools to sequester atmospheric CO_2 is influenced by crop productivity, which is often optimized using mineral N fertilizers (Khalsa et al., 2020; Triberti et al., 2008). Yet, the use of N fertilizer may increase soil production of N_2O, a greenhouse gas with nearly 300 times more global warming potential than CO_2 (Cayuela et al., 2017; Eggleston et al., 2006). To quantify the potential benefits and tradeoffs of OM amendments like compost in agricultural soils, both changes in SOC content and emissions from greenhouse gasses (GHGs) must be considered.

In recent years, we have seen a revitalized interest in compost use in agriculture as a method to reduce waste and as a way to increase soil nutrients and carbon. With legislation like California's Short-Lived Climate Pollutant Reduction Strategy (SB 1383) that recently came into effect in 2022, it is anticipated that compost from food waste for use on-farm may become more widely available (Harrison et al. 2020). Recent studies about OM inputs have focused on impacts to soil C sequestration, soil structure, and nutrient availability or retention (Erana et al., 2019; Goswami et al., 2017; Sharma et al., 2017; Tautges et al., 2019). The influence of compost on cropping systems has largely been investigated in grains and row crops or grasslands, with few studies focusing on extended periods of application in perennial crops like orchards (Hargreaves et al., 2008; Khalsa et al., 2022; Khalsa & Brown, 2017). Complex OM and C sources contributed by compost can provide the resource potential to support a diverse well-structured soil community with increased biomass and activity (Liu et al., 2016; Martínez-Blanco et al., 2013a). Microbial activity is generally responsible for most soil N_2O, which is a product or intermediate of enzymatic processes including denitrification, nitrification, and nitrifier denitrification (Zhu-Barker & Steenwerth, 2018).

In California, almond orchards are a major cropping system, with over 619 thousand hectares planted in the state in 2019 (CDFA, 2020). Perennial cropping systems (orchards and vineyards) can contribute GHGs to the atmosphere from soil generated emissions derived from the distribution of fertilizer and irrigation (Aguilera et al., 2015; Cayuela et al., 2017; Kendall et al., 2015; Smart et al., 2011; Steenwerth & Belina, 2010; Yu et al., 2017, 2019). In orchards, nitrous oxide (N_2O) has been the focus of investigation, as carbon-based GHGs (CO_2 and methane, or CH_4) are generally considered offset by the long tree lifespan (~25 years as primary producers) and their CO_2 fixation (Linquist et al., 2012; Marvinney et al., 2015; Smith et al., 2007).

In California's Mediterranean climate, irrigation controls soil water content during the dry, growing seasons in annual and perennial cropping systems. Soil water content influences soil-derived N_2O emissions (Maybe add Stanford and Epstein 74, Myers et. al 82, ref). Specifically, soil water contents exceeding 70% water filled pore space (WFPS) are associated with increased N_2O from denitrification, although when water content nears saturation the anoxic conditions favor complete denitrification and reduced N_2O production (del Prado et al., 2006; Zhu-Barker & Steenwerth, 2018). Under aerobic conditions or soil water contents below 70% WFPS, N_2O production is often attributed to nitrification, but may also evolve from abiotic process such as chemodenitrifiaction and hydroxylamine decomposition (Zhu-Barker & Steenwerth, 2018). However, the influence of soil water on N_2O production is not a consistent correlation, and the optimal WFPS for soil N_2O can vary depending on clay content (Schjønning et. al, 2003). Franzlubers (1999) reported maximum nitrification rates at an average of 42% WFPS, while Stanford and Epstein (1974) reported maximums between 80% - 90% WFPS and Schjønning et.al around 60% - 80% WFPS (Franzlubers, 1999; Stanford and Epstein, 1974; Schjønning et. al, 2003) Inorganic N fertilizers, supplied through fertigation, provide substrate for dissimilatory nitrate reduction (denitrification), and ammonia oxidation (nitrification) that may produce N_2O in the soils (Bock et al., 1986; Burford & Bremner, 1975; Wrage et al., 2001). Substrate availability has been identified as the most limiting factor for microbial N_2O production in soils not limited by water, thus the application of fertigation provides water and substrate to the soil potentially reducing limitations for soil N_2O production (Stark and Firestone, 1995).

Incorporating compost as an agricultural soil amendment may have varying effects on soil N_2O emissions depending on soil types, N availability, types of compost and application rates (Inubushi et al., 2000; Senbayram et al., 2009). Decreased emissions, likely from reduced N-mineralization rates and increased immobilization, can occur when compost is included in a soil management program (Dalal et al., 2010; Nyamadzawo et al., 2014; Senbayram et al., 2012). However, increased N_2O emissions derived from inorganic N applied as fertilizers can result from soil amended with compost, particularly in sandy soils (Zhu et al., 2013; Zhu-Barker et al., 2015). The process of composting organic material produces N_2O emissions, which may be partially controlled by composting methods (Yang et al., 2019). The other benefits of diverting residues away from the landfill include avoiding the demand for limited space and the need to design, locate and engineer new landfills (Beck-Friis et al., 2000; Martínez-Blanco et al., 2013b). Studies indicate that soils amended with compost have improved soil parameters (e.g. aggregation and stability, soil structure, water infiltration and holding capacity) through increased SOM and increased degradability of available organic C in the soil (Martínez-Blanco et al., 2013b). The degradability of organic C in soils can influence the activity of nitrifiers and denitrifiers, and thus the N_2O production in the soil (Graham et al., 2017; Senbayram et al., 2012; Zhang et al., 2014). This can be particularly relevant when inorganic N concentrations are low and microbial immobilization competes for available N, which may occur when limited quantities of N fertilizer are applied at any given time (Blankenau et al., 2000; Senbayram et al., 2012).

Studies to assess N_2O emissions from California almond orchards show broad variation in results, which is expected considering typical heterogeneity of soil characteristics and associated N_2O emissions found at spatial scales ranging from microsites in pores to landscapes where almonds are grown (Figure 3.1) (Bouwman, 1996; McClain et al., 2003; Zhu-Barker & Steenwerth, 2018). The almond industry has increasingly pursued management strategies to reduce water use and N loss (Almond Board of California, 2021; Baram et al., 2016; Goldhamer & Fereres, 2017; Rudnick et al., 2021; Wood et al., 2022). These include incorporating new irrigation technology and emphasizing nutrient use efficiency practices (Almond Board of California, 2021). The common use of micro irrigation systems, including fanjet micro sprinklers and drip systems, to effectively distribute irrigation water to the trees is also frequently being used to increase efficiency of fertilizer distribution (fertigation) in agricultural systems (Baram et al., 2018; Lopus et al., 2010).

Nutrient programs meeting crops' physiological demands through frequent, targeted fertilizers applications may optimize applied nutrient use efficiency and yield based GHG emissions, which is a metric balancing the N_2O and CH_4 emissions from agricultural systems with the crop yields of the system (Mosier et al., 2006; Muhammad et al., 2009, 2015; Van Groenigen et al., 2010). The potential for frequently applying N fertilizers at low concentrations (High Frequency-Low Concentration [HFLC]) to reduce N losses has been shown successful in non-perennial crop production (Abdelraouf & Ragab, 2018; Assouline et al., 2006; Farneselli et al., 2015; Rajput & Patel, 2006; Silber et al., 2003; Thompson et al., 2003). HFLC has the potential to reduce nitrate leaching from California almonds to groundwater, and under HFLC nutrient management, N_2O losses are less with nitrate-based fertilizers compared to ammoniacal fertilizer (Baram et al., 2016; Wolff et al., 2017). Our previous research indicates that HFLC has the potential to reduce soil N_2O emissions in California almond orchards, such that emissions from HFLC drip application fall in range or generally below other almond orchard N_2O studies (Figure 3.1) (Nichols et al., Chapter 1).

This study examines N_2O emissions from an almond orchard utilizing HFLC drip fertigation and receiving long-term (7 years) compost application. Nitrous oxide emissions are compared with an adjacent HFLC drip fertigation almond orchard which received no compost applications, while all other management practices were held constant. Prior evidence supporting the use of HFLC in crop production to reduce N losses exists in the literature, and the role of compost use in agricultural soils in contributing to N_2O emissions has been investigated under a broad range of parameters (Abdelraouf & Ragab, 2018; Assouline et al., 2006; Dalal et al., 2010; Farneselli et al., 2015; Inubushi et al., 2000; Nyamadzawo et al., 2014; Rajput & Patel, 2006; Senbayram et al., 2009, 2012; Silber et al., 2003; Thompson et al., 2003; Zhu et al., 2013; Zhu-Barker et al., 2015). However, there exists a knowledge gap regarding the potential for HFLC nutrient programs in combination with compost applications to impact N_2O emissions from almond orchards. The objectives of this study are to inform nutrient and floor management decisions regarding HFLC strategy and the use of compost that can minimize nutrient losses and decrease potential greenhouse gas production in the form of N_2O from almond orchards in California's Central Valley. We hypothesize that the increase in SOM developed from repeated years of compost applications will reduce the rate at which inorganic N is metabolized into N_2O gas and emitted to the atmosphere. The results of this study will provide growers a greater understanding of the potential influence compost applications within a HFLC drip fertigation system may have on N losses to the atmosphere.

Methods

Research site

The research site is located approximately 8 km west of Modesto, California (37°37'38.17" N 121° 5'21.57"W) on a 10.5 hectare (ha) almond orchard (270 meters by 395 meters). The almond (Prunus *dulcis*) orchard site was replanted in 2012 with Nonpareil cultivars interplanted with Aldrich and Carmel cultivars, all grafted on 'Nemaguard' peach [Prunus *persica* (L.) Bratsch] rootstock. Since replanting, the eastern 5 ha has received annual surface applications of compost at the conclusion of each growing season. Compost developed from yard trimmings (Recology Inc.) was top dressed using a surface spreader at ~38 tonnes/ha annually after harvest (October or November) since 2012. Application timing and rate was determined by the grower as part of their orchard floor management program. According to analysis provided by the compost producer and conducted by Soil Control Labs (Watsonville, Ca), the compost averaged about 20% organic C, 1.6% total N, and a C:N ratio of approximately 13, with a pH around 8.50 and soluble salts (electrical conductivity) around 4.4 ds/m.

On site, trees are 4.3 m apart along the row, with 6.4 m between rows, and irrigated by surface drip hose with embedded (0.07 liters per minute) emitters every 3.7 m. The effective root zone of the almond orchard is identified typically as the top 1 m of the soil profile, where most (>90%) of the roots are located, with few roots observed greater than 2.5 m deep in the soil profile (Baram et al., 2016). The orchard at the study site is mapped as Oakdale sandy loam (*Coarse-loamy, mixed, active, thermic Mollic Haploxeralf*), a well to moderately well-drained soil composed of alluvial deposits (Soil Survey Staff, url:https://casoilresource.lawr.ucdavis.edu/gmap/, accessed 2021).

The climate in California's Central Valley is semi-arid, characterized by warm, dry summers and cool winters. Mean annual precipitation is 24.2 cm (2015-2019), most of which occurs from December to March, with mean summer monthly temperatures ranging from 13.3 ℃ to 32.5 ℃ and mean winter monthly temperatures ranging from 3.4 ℃ to 15.2 ℃ (2015-2019, California Irrigation Management Information System [CIMIS], Modesto-San Joaquin Valley Station 71, url: http://www.cimis.water.ca.gov, accessed January 18, 2020).

Experimental Design

The study was conducted during the 2019 almond growing season (December – August), in one 10 ha orchard divided in half into two treatment blocks. Since replanting in 2012, as indicated, the eastern block received compost ('compost') annually at a rate of ~38 tons/ha during October or November depending on harvest dates. The western 5 ha block ('no-compost') did not. All other management practices were consistent between treatment blocks, representing standard practices for the almond industry in the Central Valley of California. During the 2019 season, the orchard blocks received a total of approximately 183 kg N/ha over 13 fertigation events through a drip irrigation system using high frequency-low concentration irrigation (HF-LC). HF-LC is a fertigation strategy during which all the fertilizer is applied through the irrigation system more frequently than the industry standard of dry fertilizer surface applied approximately four times during the growing season. The orchard began HF-LC nutrient management in 2018, and total amounts of N and irrigation were adjusted in response to anticipated tree demand, and grower-observed climatic conditions (Muhammad et al., 2009, 2015). Fertilizer N applied at each of 13 events (March-July) during 2019 ranged from 4.5 kg N /ha to 28.0 kg/ha, applied equally to each treatment block. Fertigation was applied simultaneously on the same dates in both treatment blocks, and irrigation was not applied without fertilizer during the season. Delivery of the soluble fertilizer, urea ammonium nitrate (UAN 32) or calcium ammonium nitrate (CAN 17) depending seasonal growth demands, via the drip system was controlled by a precision irrigation system (pH Technologies LLC), which facilitated the grower's use of HF-LC.

Gas Sampling and Soil Data

This study considers 2 treatments: soil receiving compost amendment annually 'compost', and soil that did not receive annual compost amendment 'no compost'. Within each treatment, greenhouse gas emissions, soil gravimetric water content, soil temperature, and soil inorganic N were monitored in three replicates via a chamber collar transect arrays as described below (Figure 3.2). Each chamber represents the gaseous flux from the rectangular surface area represented by distance from the drip emitter and space between emitters (detailed below). This provides an estimate of gaseous flux from one emitter per array spatially representing the different zones of the orchard floor, and three replicate emitters per orchard treatment (Baram et al., 2018).

Gaseous flux rates of the greenhouse gas nitrous oxide (N_2O) were measured using the closed static chamber method (Livingston and Hutchinson, 1995). This methodology utilizes semi-permanent placement of collars in the soil surface, upon which chambers are placed during sampling events, to minimize soil disturbance during sampling. Within each treatment, PVC collars were placed in three treatment replicate arrays (Figure 3.2). Each array consists of three collars placed in a transect perpendicular to the row, adjacent to a drip emitter at the head of the berm to near the center of the alleyway between the tree rows. Collars were installed at distances from the emitter to represent three zones of orchard floor: berms where trees are planted (0cm), the edge transition zone from berm to alleyway (50cm), and the center of the alleyway (150cm). Each collar was 20 cm in diameter, 8 cm tall and installed 5 cm into the soil, leaving 3 cm above the soil surface.

Gas samples were taken 1-3 days following fertigation events and periodically during the 2019 growing season. During the winter months of January-February, data were not collected as no fertigation events occurred. On collection days, static chambers constructed according to Parkin and Venterea (2010), each with a volume of 3.5 liters, were placed on preinstalled collars for a total sampled volume of 4.5 liters. Ambient gas samples were collected at time 0, and gas was extracted from chambers at 10 and 20 minutes. During sampling events, one ambient atmospheric gas sample representing time 0 was collected at each replicate transect array at the moment the chambers were closed onto the collars. Chamber samples were then collected at 10 min and 20 min following the ambient (time 0) sample from each chamber along the transect array. This sampling process was repeated for each replicate transect array in both the compost and 'no-compost' amendment soils. All samples were manually extracted from chambers using hypodermic needles with a 20 cm^3 syringe and injected into 12 cm^3 evacuated glass vial exetainers (Exetainer®, Labco Limited, Buckinghamshire UK) for transportation. Samples were analyzed using a gas chromatograph furnished with a ^{63}Ni electron capture detector for measurement of GHGs (model GC-2014, Shimadzu).

Simultaneous to gas collection, volumetric soil water content and soil temperature were collected adjacent to each collar in the top 5 cm of soil using a ProCheck Decagon Device with a 5TE sensor (Decagon Devices, Inc.). Additionally, soil samples (0-30 cm) were collected from each treatment on each collection day using a 2 cm diameter soil core. Soil samples (approximately 90 cm^3) were collected adjacent to each collar from one replicate transect array each collection day, alternating which replicate was sampled each day. Each soil sample was homogenized, and a subsample (ca. 5 g) was placed into 50 ml of 2M KCl solution and analyzed for nitrate and ammonium concentrations colorimetrically (Alef & Nannipieri, 1995; Kempers & Kok, 1989; Miranda et al., 2001).

Soil Sampling

In August 2019, soil in each treatment block was sampled for physical and chemical characterization (Table 3.1). Samples were collected near the chamber arrays (n=3 per treatment), weighed in the field and transported in aluminum containers to the lab for analysis. Soil samples were air dried, passed through a 2mm sieve and analyzed for particle size composition as determined using the pipette method (Miller & Miller, 1987). Sieved samples were also sent to the UC Davis Analytical Lab for pH, electrical conductivity (EC), total C and total N (AOAC, 1997; Rhoades, 1982; Richards, 1954). Bulk density was measured by collecting soil sub-samples (ca. 250 cm3) using brass rings (ca. 5.08 cm height, 7.94 cm diameter). These were weighed in the field, placed in aluminum containers and oven dried at 105 °C for 48 h (until steady weight was achieved) to determine the bulk density.

Gaseous Emissions Calculations

Linear regressions of chamber concentration were used to calculate gas flux rates (q) [g cm^{-2} h^{-1}] in addition to the ideal gas law according to:

[1]	$q = \frac{dC_{gas}}{dt} * \frac{V_{chamber}}{A_{chamber}} * \frac{P}{RT} * M_w$

where c_{gas} is the measured gas concentration [µl l^{-1}], t is time [hour], $V_{chamber}$ [cm^3] and $A_{chamber}$ [cm^2] are the chamber volume and surface area, respectively, P is the ambient pressure [0.988 atm], R is the gas law constant [0.08206 l atm mol^{-1} K^{-1}], T is the temperature [K], and M_w is the molecular weight of the gas [g mol^{-1}]. Daily flux values were estimated assuming the measured fluxes were the daily average (Alsina et al., 2013; Baram et al., 2018; Schellenberg et al., 2012).

This approach assumes each measurement position was representative of the gas flux of the area of a rectangle of the orchard zone in which a sample was collected (Q_{Zone}). The rectangle was based on the distance between the collars from emitter to alleyway, and the distance between emitters along the drip line. In drip irrigation systems, the majority of the wetted area, and resulting N_2O emissions, is near the source (the emitter) (Alsina et al., 2013). Thus, the sampling locations represent areas of the orchard floor receiving the most fertigation, some fertigation, and minimal fertigation, allowing the scaling to incorporate the spectrum of orchard floor conditions following fertigation events.

Nitrous oxide emission measurements around the irrigation emitters were scaled to the orchard level using a unit tree area of 1.98 m^2. Calculated emissions were then summed and multiplied by the given representative areas to give total N_2O emission per tree:

[2]	$$Q_{Tree} = \sum_{i=0}^{r_{max}} q_i(i \times x)$$

where Q_{Tree} is total emission per tree [ng N_2O-N h^{-1}], q_i is the emission rate measured at the i^{th} collar [ng N_2O-N cm^{-2} h^{-1}], i is the distance from the emitter (cm), x is the length of the row between emitters (cm), following Baram et al., 2018.

Cumulative orchard emissions were calculated by averaging the daily Q_{Tree} from each sampling day for each treatment. Using the number of trees planted per hectare in the orchard, an average emission rate of N_2O-N per hectare for each sampling day was calculated. Cumulative growing season emissions were then determined by adding each sampling day's N_2O-N emissions per hectare to the previous total emissions from the prior sampling days.

Statistical Analysis

The effect of compost on soil N_2O emissions in the orchard was analyzed as daily emissions from orchard zone (Q_{Zone}) by analysis of variance (ANOVA) using a mixed model for repeated measures ($p<0.05$). The mixed model was repeated with and without the inclusion of soil temperature, soil water content and inorganic N content as covariates. These covariates did not improve the model (data not shown). The mixed model held orchard floor treatment, date, and orchard floor zone (zone) as fixed effects, and replicate array as a random effect. The ANOVA analyzed whether the main effects of treatment ('compost' vs. 'no-compost'), sampling date and zone, and the interaction effect between these factors are statistically significant ($p<0.05$). Variables were tested for normality and homogeneity of variances (Shapiro-Wilk's method), the assumptions necessary for ANOVA, and a natural log transformation was conducted on N_2O emissions. Post-hoc pairwise comparisons were conducted using Kenward-Roger method and Tukey adjustment based on *a priori* hypotheses that sample events at the onset of fertigation season (March) would have greater variability in N_2O fluxes. Soil characteristics that were sampled on one sampling event (pH, EC, total N, total C, and bulk density), and cumulative total N_2O emissions were evaluated using a paired T-test between the compost amended soil and 'no-compost' soil for significant differences between the means. Untransformed emissions data were plotted. All statistical analyses were conducted in R version 4.0.3 (R Core Team, 2020), using lme4 for model analysis (Bates et al., 2014), emmeans for post-hoc analysis (Lenth, 2020) and ggplot2 for figures (Villanueva & Chen, 2019).

Results

Soil characteristics did not differ between 'compost' and 'no-compost', although there was a trend for values to be greater in 'compost' than 'no-compost' (Table 3.1 and supplemental Table 3.1). Soil pH in the compost amended block measured 6.68±0.36 (n=3), while the 'no-compost' soil was 6.16 ±0.57 (n=3) (t = 1.266, df = 2, p-value = 0.333) (Table 3.1**)**. Electrical conductivity in 'compost' tended to be greater (0.396±0.139 ds m^{-1} (n=3) than in 'no-compost'(0.293±0.245 ds m^{-1}, n=3, t = 1.665, df = 2, p-value = 0.2378). Total N and total C in 'compost' (0.13%±0.02% and 1.34%±0.20%, respectively; n=3) tended to be greater than 'no-compost' (0.08%±0.03% and 0.81±0.29, respectively; n=3) (total N: t = 1.7104, df = 2, p-value = 0.2293; total C: t = 1.9905, df = 2, p-value = 0.1848). 'Compost' tended to have a lower bulk density (1.48±0.09 g cm^{-3}) 'no-compost' soil (1.52±0.11 g cm^{-3}, n=3) (t = -3.2088, df = 2, p-value = 0.08493).

During the 2019 growing season (December - August), we observed mean N_2O fluxes ranging from 0.29 g N_2O-N ha^{-1} day^{-1} to 5.5 g N_2O-N ha^{-1} day^{-1} in the orchard soils. The compost amended soil ranged from 0.34 to 3.7 g N_2O-N ha^{-1} day^{-1} while the 'no-compost' soil ranged from 0.29 to 5.5 g N_2O-N ha^{-1} day^{-1} (Figure 3.3). The interaction between treatment × sampling date was significant (Table 3.2, $p<0.05$). In December before tree flowering and prior to initiation of the seasonal fertigation regimen, mean N_2O fluxes were similar (supplemental Table 3.2, p=0.2428) between 'compost' and 'no-compost' treatments (0.54±0.22 and 0.55±0.23 g N_2O-N ha^{-1} day^{-1} respectively, n=3). In March, as temperatures increased and the trees became more active physiologically, sampled fluxes began to differ between treatments. After the initiation of fertilizer applications in March, 'no-compost' fluxes diverged from 'compost', such that 'no-compost' tended to have higher fluxes (up to 2.75-fold) than 'compost' (Table 3.2). One sampling event in April yielded very similar N_2O fluxes (p=0.70) between the treatments ('no-compost': 1.81 ± 0.18 g N_2O-N ha^{-1} day^{-1} and 'compost': 1.78 ± 0.30 g N_2O-N ha^{-1} day^{-1}), while the other sampling events throughout the growing season tended to show differences in fluxes.

Relationships between N_2O emissions and soil conditions, or temperature, volumetric water content and inorganic N pools between treatments, were not significant when fitting with linear regression (supplemental Figures 3.1 - 3.3). When inspecting the relationship between soil temperature and flux measurements, we see similarities between the 'compost' and 'no-compost' soils (Figure 3.4). Soil temperatures during flux sampling events in both treatments ranged from 15.5 °C to 35.2 °C. Both treatments show a peak in N_2O flux near 23-25 °C. On the upper end of the measured temperature range, the 'no-compost' soils tend to have higher N_2O fluxes than the compost-applied soils.

The volumetric soil water content during soil N_2O flux sampling ranged from 0.7% to 30.6% (Figure 3.5). The 'no-compost' treatment had peak fluxes at soil moisture contents below 5% and near 20%, while the 'compost' treatment had peak fluxes at around 15%. At volumetric soil water contents greater than 15%, the fluxes from the 'compost' treatment are more variable compared to those occurring at volumetric soil water contents less than 15%. At less than 5% and greater than 15% volumetric soil water contents, N_2O emissions in the 'no-compost' treatment are more variable than they are from those occurring at 5% -15% volumetric soil water content range.

The concentration of inorganic N (NH_4^+-N + NO_3^-–N) in the soil during N_2O flux sampling ranged from 2.5 to 59.4 mg of inorganic N per kg of dry soil and was generally below 20 mg kg^{-1} in both treatments (Figure 3.6). Samples from the 'no-compost' and 'compost' treatments both recorded the highest fluxes when inorganic N content in the soil was below 10 mg kg^{-1} of soil. Some inorganic N samples approached 60 mg N kg^{-1} soil, but high inorganic N concentrations did not correlate significantly with high N_2O fluxes, as indicated by linear regression (supplemental Figure 3.3). There was no clear relationship between inorganic N and N_2O fluxes in the orchard soils (Figure 3.6 and supplemental Figure 3.3).

The interaction effect of Treatment × Orchard Zone was not significant for N_2O emissions ($p = 0.86$), while the interaction effect of Sampling Date × Orchard Zone was significant ($p<0.01$) (Table 3.2). The orchard zone in which the collar was placed (berm, alley edge, or alley center) is associated with various distances from the drip emitters, which distribute fertigation to the soil. Generally, the alley center is further from the source of irrigation water and fertilizer (i.e. the emitters) and receives less water during those events. Sampling following irrigation events during climatically dry parts of the season, found sampling on the alley edge would have higher soil moisture due to spatial proximity to the source of irrigation (Figure 3.2), while soil moisture would be more even between the collar locations following precipitation events.

Cumulative measured N_2O-N emissions tended to differ increasingly between treatments as the growth season progressed, with the 'compost' treatment measuring below the 'no-compost' treatment (Figure 3.7). Cumulative total N_2O-N emissions in the 'compost' treatment was lower than the cumulative total in the 'no-compost' treatment ($t = 5.3011$, $df = 2$, p-value = 0.03379) when sampling concluded in August. At the season's end (August), cumulative emissions in the 'compost' treatment (11.5 g N_2O-N ha^{-1}) are approximately 8 g N_2O-N ha^{-1} below the cumulative emissions from the 'no-compost' treatment (20.1 g N_2O-N ha^{-1}).

Discussion

Investigations of N_2O emissions from almond orchard soils in the Central Valley of California have observed fluxes ranging from less than 0.001 g N_2O-N ha^{-1} day^{-1} (Schellenberg et al., 2012) to greater than 105 g N_2O-N ha^{-1} day^{-1} (Alsina et al., 2013), across various fertilizer and irrigation programs (Figure 3.1). Schellenberg et al. (2012) measured soil N_2O fluxes from fertigation of an orchard planted in Milham sandy loam (Fine-loamy, mixed, superactive, thermic, Typic Haplargids) fertilized with UAN 32 and CAN 17. The study provided 224 kg N ha^{-1} of annual N input split into four events distributed through micro-sprinklers and observed peak emissions of 25.5 g N_2O-N ha^{-1} day^{-1}, nearly five times the peak observed in our study (5.5 g N_2O-N ha^{-1} day^{-1}). Alsina et al. (2013) observed peak fluxes exceeding 100 g N_2O-N ha^{-1} day^{-1} in their study of 235.5 kg of N ha^{-1} applied through drip and micro-sprinklers during five fertigation events to an almond orchard planted in deep, well drained gravelly sandy loam in the Arbuckle series (fine-loamy, mixed, superactive, thermic Typic Haploxeralf), again well above our peak emissions. Wolff et al. (2017) recorded peak emissions greater than 35 g N_2O-N ha^{-1} day^{-1} in a standard fertigation program and peak emissions exceeding 30 g N_2O-N ha^{-1} day^{-1} in a high frequency fertigation program, in an almond orchard planted in Milham sandy loam (fineloamy, mixed, superactive, thermic, Typic Haplargids) receiving 336.3 kg N ha^{-1} $year^{-1}$. All of these studies, including ours, recorded fluxes below 1 g N_2O-N ha^{-1} day^{-1} in almond orchards. Our range of daily N_2O emissions falls on the lower end of the almond orchard studies, however a direct comparison would be confounded by the potential influences of variable management practice and edaphoclimatic factors on soil N_2O production, particularly because to our knowledge no other studies have considered N_2O emissions in cropping systems applying compost while utilizing HFLC drip fertigation.

The various processes leading to the production and emission of soil N_2O (i.e. nitrification, denitrification, nitrifier-denitrification, hydroxylamine decomposition and chemodenitrification) are influenced by a number of factors such as pH, organic matter, oxygen (O2) availability, soil water content, soil texture, and supply of inorganic N (Zhu-Barker & Steenwerth, 2018). The heterogeneity of these factors, across soil landscapes and within soil matrices, controls the variability in the observed soil N_2O fluxes (McClain et al., 2003). Peak soil N_2O fluxes are often considered in relation to hot spots or hot moments. These are temporary significant increases in N_2O production above background fluxes, often associated with shifts in moisture from drought conditions to moist conditions (Barrat et al., 2021). This variability was observed in our recorded N_2O fluxes, which ranged from 0.29 to 5.5 g N_2O-N ha^{-1} day^{-1} across treatments in the orchard, which had a range of volumetric soil water content (0.7% to 30.6%) and inorganic N concentrations (2.5 to 59.4 mg of inorganic N per kg of dry soil) contributing to soil N_2O production during sampling events. This variability has been documented in other California almond orchards, which report ranges from less than 0.01 to greater than 100 g N_2O-N ha^{-1} day^{-1} (Figure 3.1) (Alsina et al., 2013; Schellenberg et al., 2012, 2012; Wolff et al., 2017).

The compost amended orchard soil measured approximately 61% higher total C content and 63% higher total N content than the 'no-compost' treatment (Table 3.1). This increase in total C and N aligns with other findings from studies on effects of utilizing organic matter, such as composted dairy manure, chicken litter, and yard green waste, as a soil amendment in almond and peach orchards (Khalsa et al., 2022; Martínez-Blanco et al., 2013; Preusch & Tworkoski, 2003). Soil bulk density tended to be lower in our compost amended orchard soils (Table 3.1), which is consistent with previous work showing the trend for organic amendments to lower bulk density and reduce compaction (Arvanitoyannis & Kassaveti, 2007; Cayuela et al., 2004; Mujdecİ, 2011; Peck et al., 2011). These effects have been observed for a wide range of organic amendments, including composted olive oil waste, biosolids, manures, and mulch as OM amendments in apple orchards, tomato fields, and olive plantations (Arvanitoyannis & Kassaveti, 2007; Cayuela et al., 2004; Mujdecİ, 2011; Peck et al., 2011).

Soil N_2O production through ammonia oxidation pathways is influenced by moisture, pH, soil texture, temperature, O_2 availability, ammonium NH_4^+ concentration, soil nitrifier activity, and bioavailability of iron (Fe) and manganese (Mn). For soil N_2O production from heterotrophic denitrification, water content is identified as the most important factor through its control on O_2 diffusion, C availability, and NO_3^- concentration (Zhu-Barker & Steenwerth, 2018). Agricultural management of irrigation, inorganic N fertilizers, and soil treatments (e.g. tillage, amendments, etc.) allow producers the potential to influence soil N_2O emissions due to the influence of these management decisions on important soil factors. The mechanisms behind flushes of soil N_2O production are still being enumerated, but water content, a primary driver of gaseous emissions, is intertwined with other influential factors like substrate availability (Barrat et al., 2021, 2022). However, we did not observe a correlation between water content nor inorganic N pools with N_2O production (supplemental Figures 3.2 - 3.3). The lack of correlation between soil N_2O emissions and measured soil parameters may be attributed to the high spatial and temporal heterogeneity of nitrification and denitrification in soil (Davidson, 1992; McClain et al., 2003; Mummey et al., 1997). Consistent with our findings, concentration of inorganic N has been observed as a poor indicator for soil N_2O production in other cropping systems (Rochette et al., 2004).

The influence of soil water content on soil-derived N_2O emissions is well documented, particularly when soil water contents exceed 60% - 70% WFPS depending on soil texture and relative gas diffusivity in the pore space (Linn & Doran, 1984; Schjønning et al., 2003). Water filled pore space is a function of soil moisture and bulk density. Organic matter amendments such as compost, have been shown to increase the water holding capacity of soil as well as decrease bulk density (Celik et al., 2010; Hargreaves et al., 2008; Hernando et al., 1989; Verheijen et al., 2019). Soil water contents above 70% WFPS and below saturation, are associated with increased N_2O from denitrification (del Prado et al., 2006; Zhu-Barker & Steenwerth, 2018). In our data we see peak fluxes occur in the 'no-compost' soil near 20%

volumetric water content (50% WFPS) and in the 'compost' soil around 15% volumetric water content (34% WFPS). Both treatments tend to have a wider range of N_2O fluxes from around 15% volumetric water content (38% WFPS in 'no-compost', 34% WFPS in 'compost' soil) to around 30% volumetric water content (75% WFPS in 'no-compost', 68% WFPS in 'compost' soil), suggesting onsite soil N_2O evolution may not be primarily denitrification. Under aerobic conditions or soil water contents below 70% WFPS, N_2O production is attributed to nitrification, but may also evolve from abiotic process such as chemodenitrifiaction and hydroxylamine decomposition, which may be the N_2O emissions we observed (Zhu-Barker & Steenwerth, 2018). In our study, bulk density tended to be lower in the compost amended soil (Table 3.1), volumetric soil water content tended to be similar among treatments, but WFPS tended to be lower in the 'compost' treatment, and we observed lower cumulative N_2O production in the compost amended soil (Figure 3.7). This suggests that reduced bulk density from compost additions creates lower WFPS in soils with similar volumetric water contents, resulting in less optimal soil conditions for denitrification. This may partially explain the lower N_2O production in the compost amended soil.

In addition to soil water content, N_2O fluxes are impacted by the availability of inorganic N (NH_4^+, NO_3^- and NO_2^-) and organic C in the soil (Senbayram et al., 2012). We did not observe a correlation between soil inorganic N concentration and N_2O fluxes (supplemental Figure 3.3), however the majority of our samples showed concentrations of NO_3^- below 20 mg kg^{-1} soil, the threshold above which Senbayram et al. (2012) observed the greatest influence on soil N_2O emissions in a laboratory incubation study on soils from long term organic and inorganic fertilizer plots. Additionally, the increased soil C we observed in the compost amended soil can function to reduce peak fluxes, particularly in the soils with <20 mg kg^{-1} of NO_3^- (Senbayram et al., 2012). While inorganic N fertilizer may contribute to increased GHG emissions, a direct correlation between reducing inorganic N inputs and the overall impact to climate change may not be clear cut. Khalsa et al. (2020) recently showed higher fertilization rates (309 kg N ha^{-1} yr^{-1} compared to 224 kg N ha^{-1} yr^{-1}) may decrease the overall global warming potential (GWP) of orchards due to soil C increases from higher leaf litter biomass, increase net N immobilization and tree efficiency of nutrient use improving productivity. They define GWP as the sum of CO2 emissions from orchard fuel use, CO2 emissions from urea hydrolysis of UAN fertilizer, soil N_2O emissions, soil CH4 oxidation, and changes in SOC from tree derived organic matter. The inclusion of compost as a soil input, as in our study, results in similar increases in SOC and net N immobilization, thus decreasing GWP of production systems using HFLC and compost amendments.

Reduced N_2O emissions associated with increased soil C may be a result of increased microbial immobilization of available N (Khalsa et al., 2020, 2022; Senbayram et al., 2012). With readily available C, microbial dynamics are likely to be limited by other substrates such as N. In turn, when inorganic N is made available through fertigation, it may be immobilized quickly making less N available as a substrate for nitrification and denitrification (Graham et al., 2017). While we did not directly measure immobilization of N in this study, the highest inorganic N concentration was observed in the ‘no-compost’ soil, although no correlation was found between N_2O emissions and soil inorganic N concentration. It is possible this is a partial explanation of the reduced production of N_2O we observed in the soil treated with compost. The ratio of C and N in organic amendments influences the turnover of microbial biomass and the mineralization of soil organic carbon and available nutrients in the soil (Li et al., 2018; Moreno-Cornejo et al., 2015; Thiessen et al., 2013). Compost additions in our study may have increased net N immobilization, reducing the availability of N for nitrification and denitrification. The availability of inorganic N provided by fertigation can reduce the magnitude of soil microbial activity generally observed in response to increases in labile C from organic soil amendments (Blagodatskaya & Kuzyakov, 2008; Chen et al., 2014; Fontaine et al., 2011). This may explain why the use of a HFLC nutrient management approach in conjunction with compost amended soil vs non-amended soil, resulted in significantly lower cumulative N_2O emissions measured during the 2019 growing season in this study (Figure 3.6).

Our results indicate that soil amended with compost may have fewer losses of N as N_2O when a HFLC nutrient management program is implemented. This finding will aid growers and regulators who are working to continue developing best management practices to optimize crop production and minimize environmental externalities. It contributes to refinement of grower best management practices for nutrient and floor management approaches to mitigate N_2O greenhouse gas emissions from almond and other deciduous cropping systems. Additionally, this information supports fulfillment of California's SB 1383 (2016) requirement to reduce the organic material disposed of in land-fills by 75% from the 2014 level. Our findings identify a viable opportunity to incorporate composted organic material into orchard floor management strategies while minimizing potential impacts to GHG emissions from the orchard floor.

Tables and Figures (See Below)

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Tables and Figures

Table 3.1. Soil characteristics.

Treatment	Sand (%)	Silt (%)	Clay (%)	Texture Class[2]	pH (1:1) [1]	EC (1:1) [1]	Total N (% mg N)[1]	Total C (% mg C)[1]	Bulk Density (g cm^{-3})
No-Compost	65.0	23.8	11.2	Sandy Loam	6.16± 0.57	0.293± 0.245	0.08±0.03	0.81±0.29	1.52±0.11
Compost	65.0	23.8	11.2	Sandy Loam	6.68± 0.36	0.396± 0.139	0.13±0.02	1.34±0.20	1.48±0.09

Means ± SD (n = 3).
[1] UC Davis Analytical Lab: AOAC, 1997; Rhoades, 1982; Richards, 1954
[2] USDA NRCS Soil Survey Texture Class

Table 3.2. Analysis of Variance (ANOVA) for effects of compost application, date of sampling, orchard zone, and the interactions of these on N_2O-N flux.

Effect	F-statistic	P value	Significance*
Treatment	7.11	0.0083296	< 0.01
Sampling Date	15.25	0.0001315	< 0.001
Orchard Zone	3.13	0.0461496	< 0.05
Treatment × Sampling Date	7.1357	0.0082264	< 0.01
Treatment × Orchard Zone	0.1467	0.8636648	n.s.
Sampling Date × Orchard Zone	3.1127	0.0468039	< 0.05
Treatment × Sampling Date × Orchard Zone	0.1445	0.8655874	n.s.

* n.s. = not significant

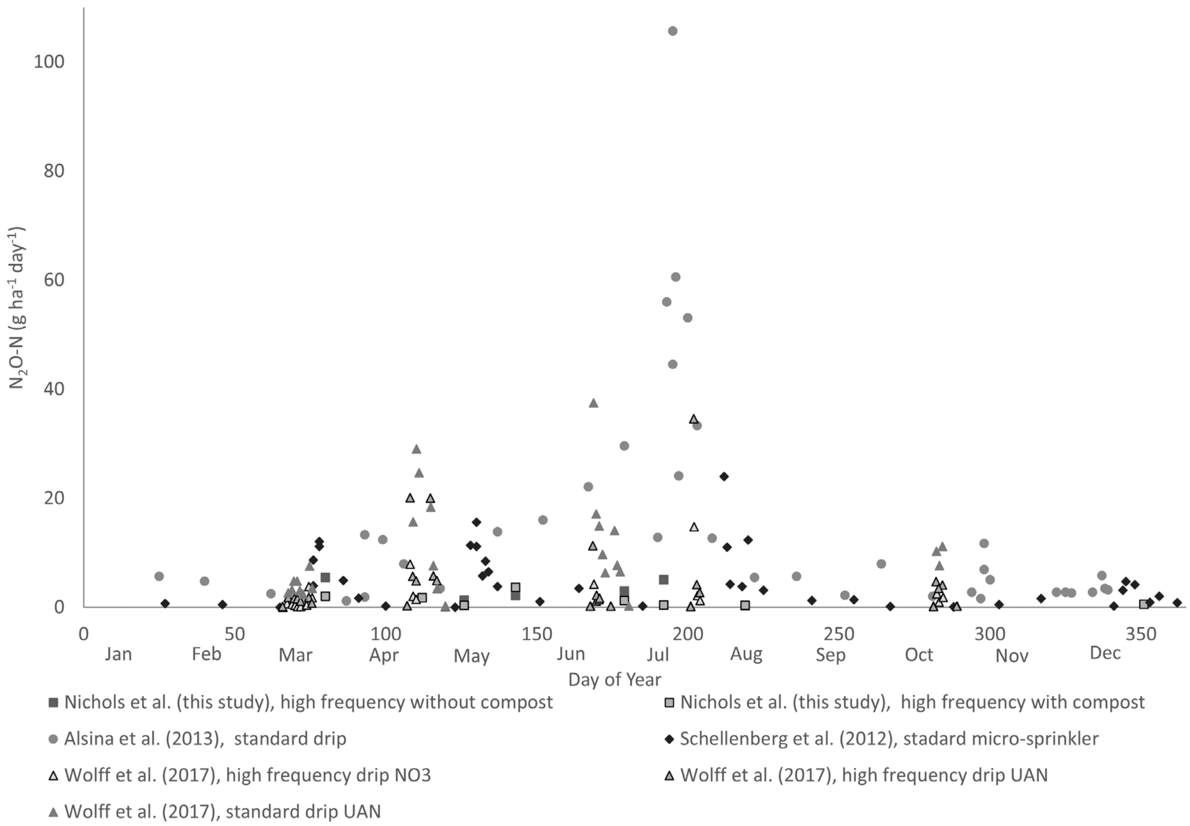


Figure 3.1: N_2O emission from almond orchards in California's Central Valley. Alsina et al. (2013) orchard received 235.5 kg of N ha^{-1} through 5 drip fertigation events; Schellenberg et al. (2012) orchard received 224 kg N ha^{-1} through 4 micro sprinkler fertigation events; Wolff et al. (20017) orchard received 336.3 kg N ha^{-1} through three different drip fertigation treatments: 20 events of NO_3-based fertilizer (high frequency NO_3), 20 events of UAN fertilizer (high frequency UAN), 4 events UAN fertilizer (standard UAN).

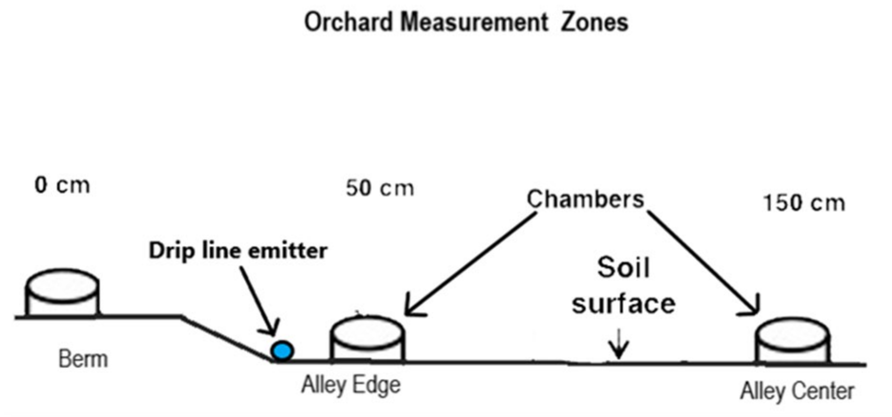


Figure 3.2: Schematic of collar placement on orchard row's berm and alley of each array associated with each sampling replicate (n=3) in each treatment ('compost' and 'no compost').

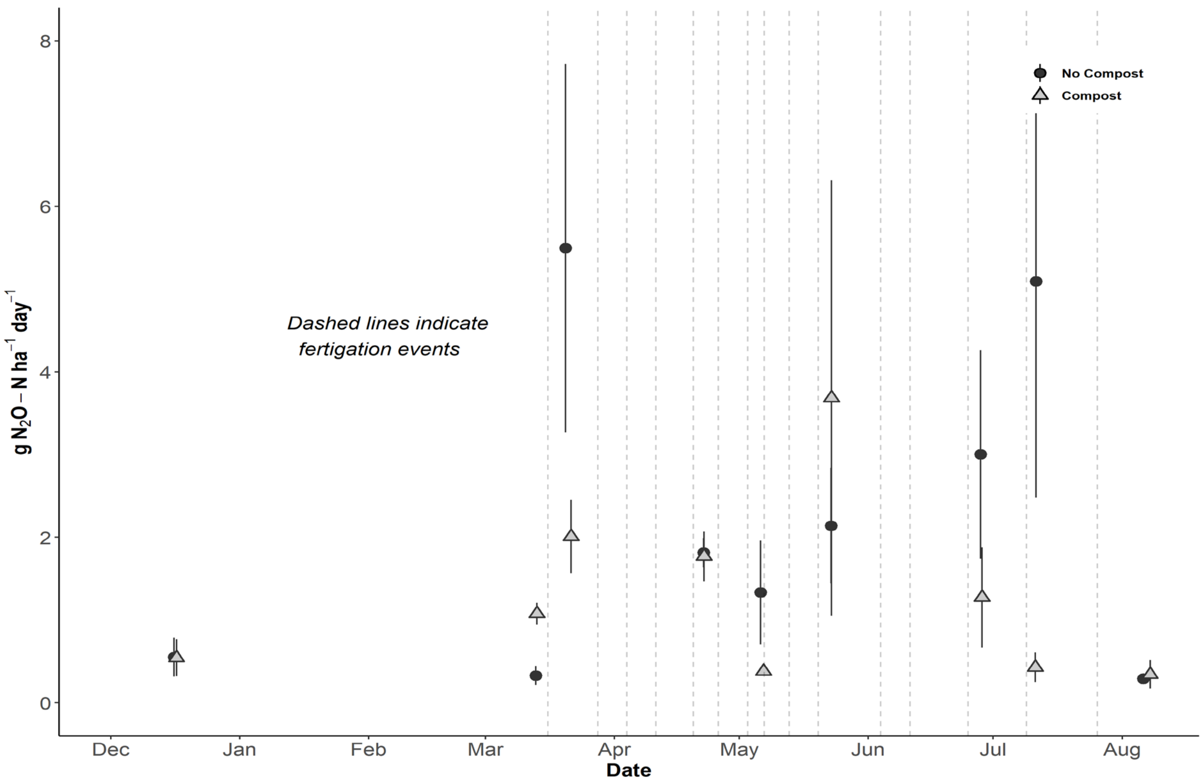


Figure 3.3: N_2O fluxes on sampling days during the 2019 growing season. Symbols represent daily means (n=3) and standard errors by treatment. Circles represent the 'no-compost' treatment, and triangles represent the 'Compost' treatment. Dashed lines show dates of fertilizer events. While fertigation amount application varied among dates, the same amount was applied to both treatments on a given date of application.

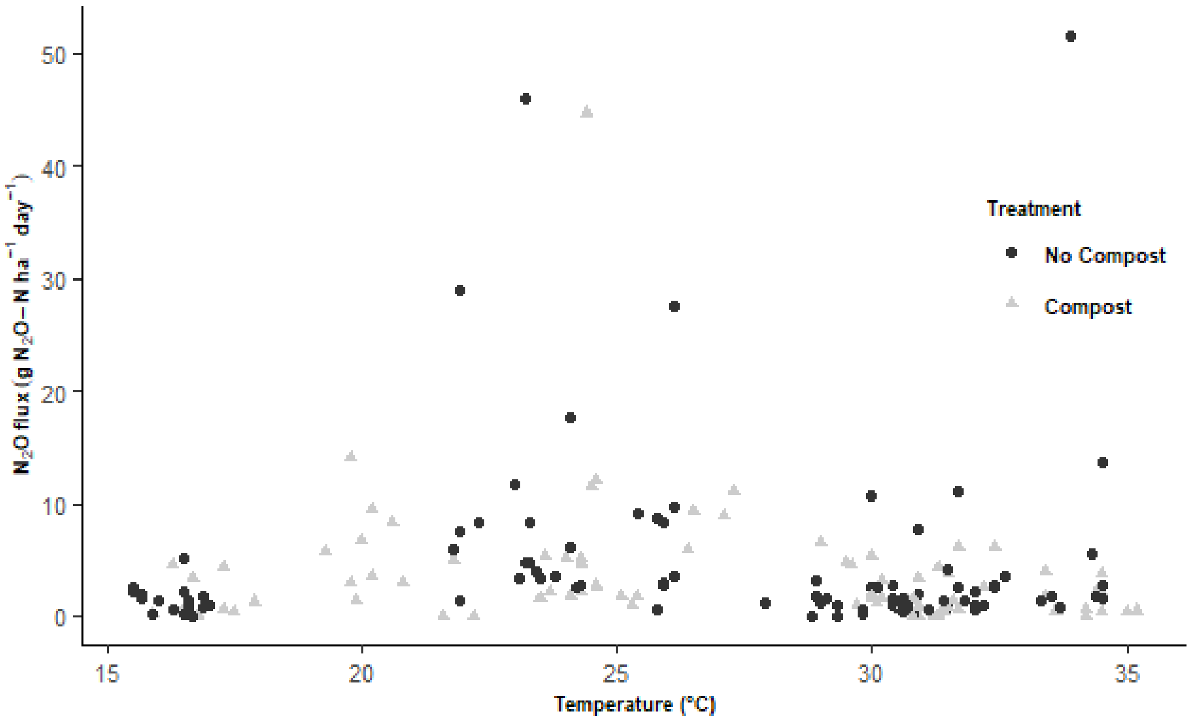


Figure 3.4: N_2O fluxes and measured temperature (°C) of soil during sampling events.

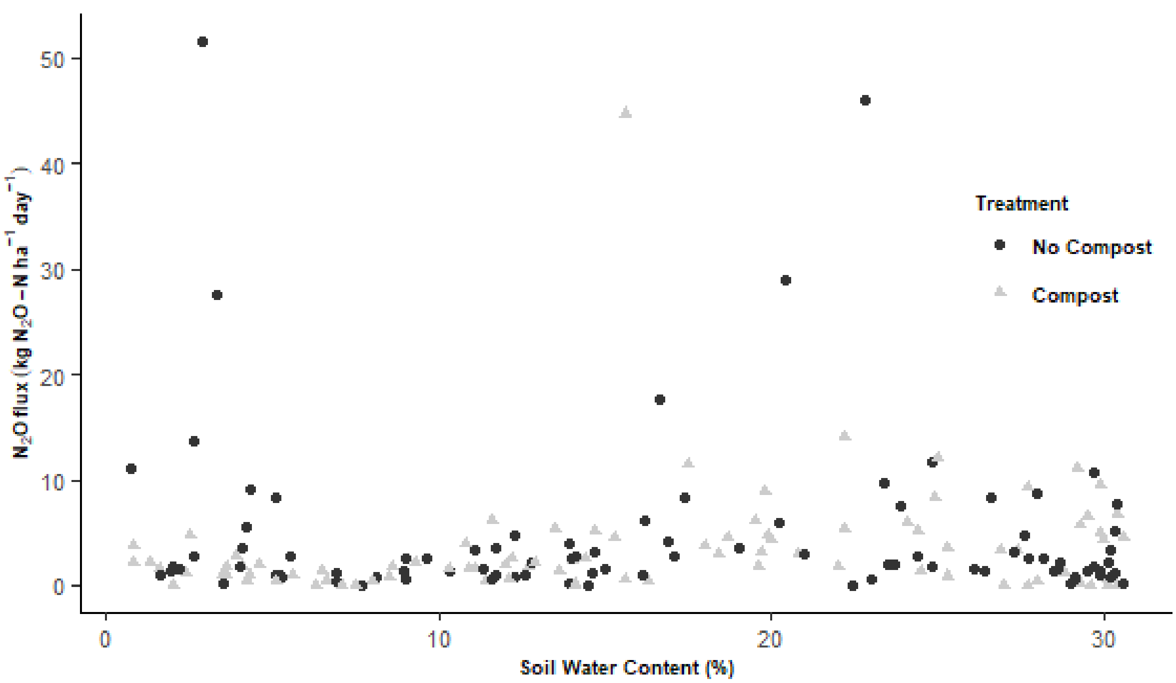


Figure 3.5: N_2O fluxes on sampling days and measured soil water content (percent, %) of soil during sampling events.

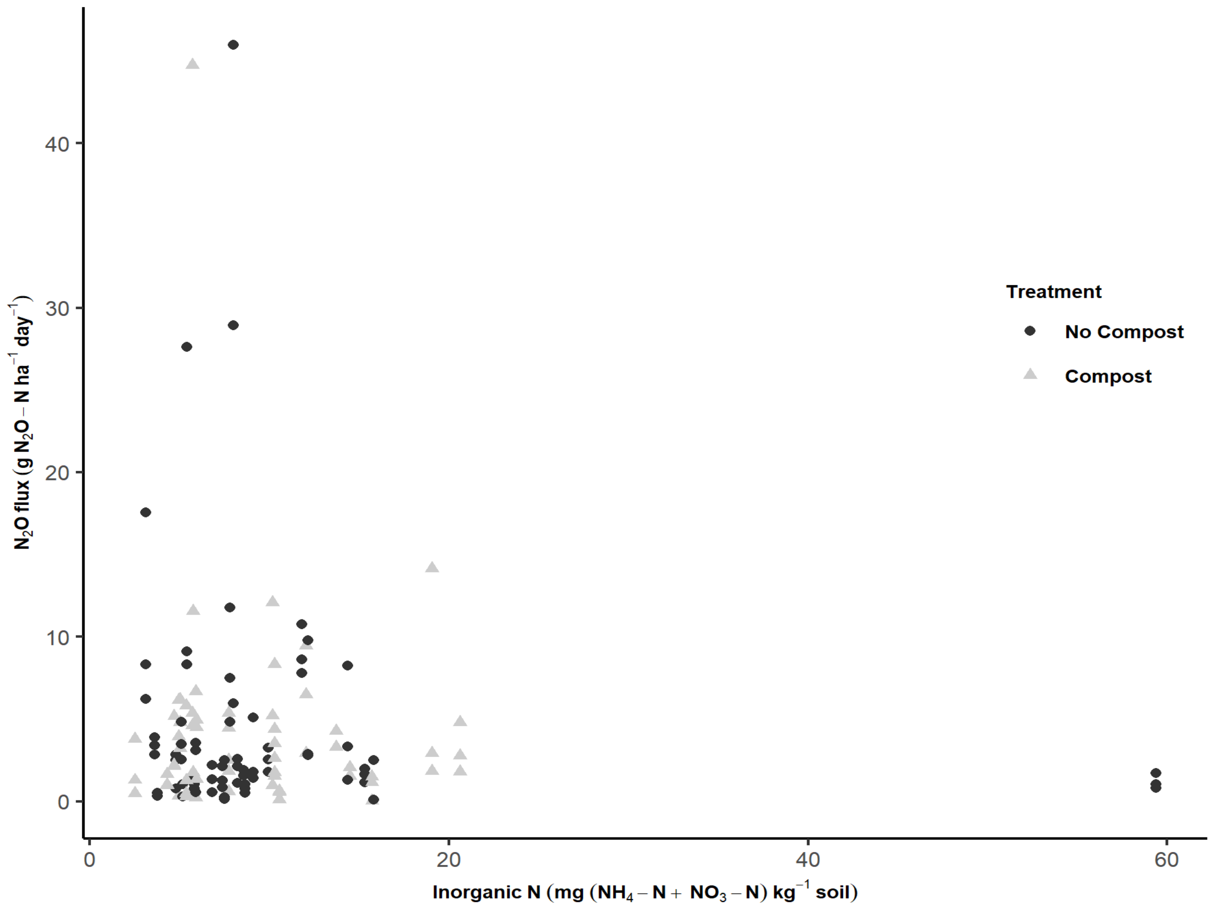


Figure 3.6: N_2O fluxes on sampling days and measured soil inorganic N content [mg (NH_4^+-N+ NO_3^{--}-N) kg soil$^{-1]}$ of soil during sampling events.

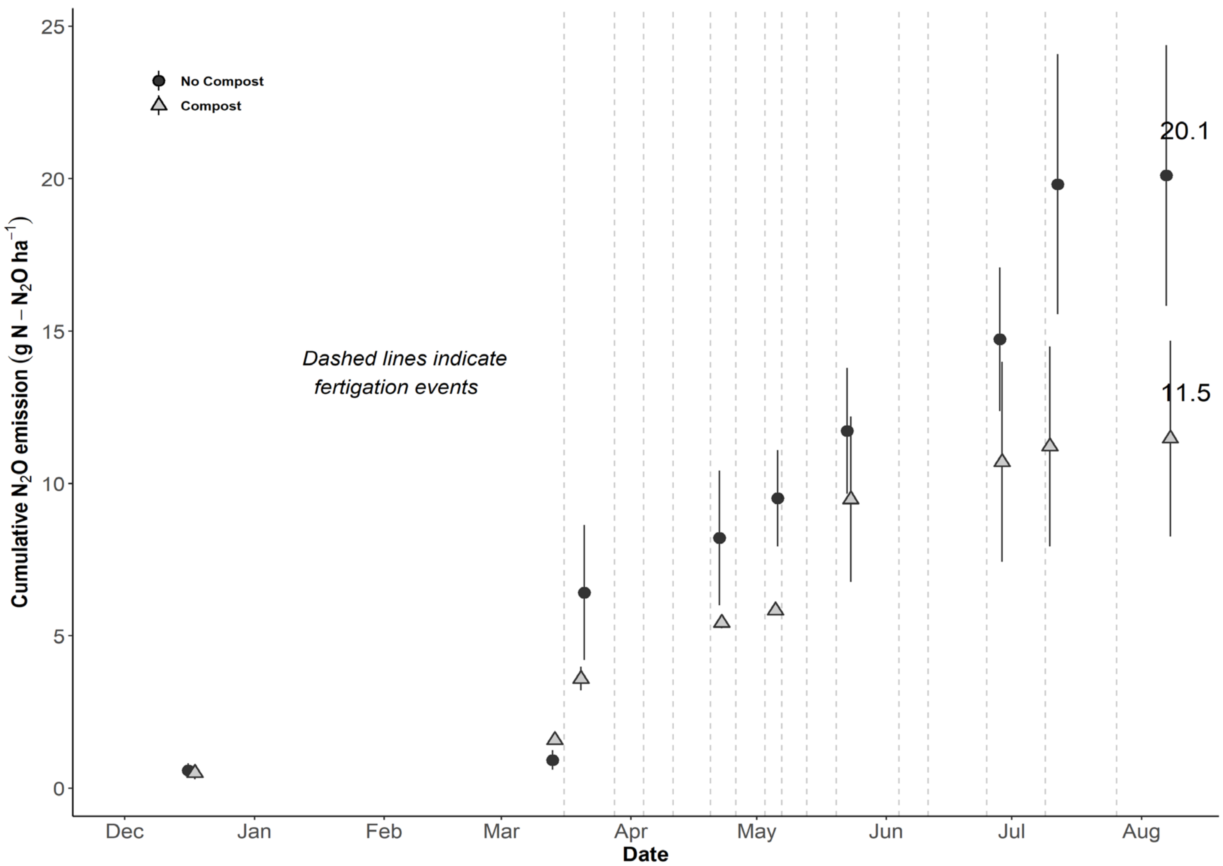


Figure 3.7: Cumulative N_2O-N production during the 2019 growing season from compost amended orchard soil (triangles) and no-compost orchard soil (circles). The numerical values written on the right side of the graph panel are the total cumulative value from each treatment in g N_2O-N ha $^{-1}$.

Chapter 3 Appendix

Supplemental Tables and Figures:

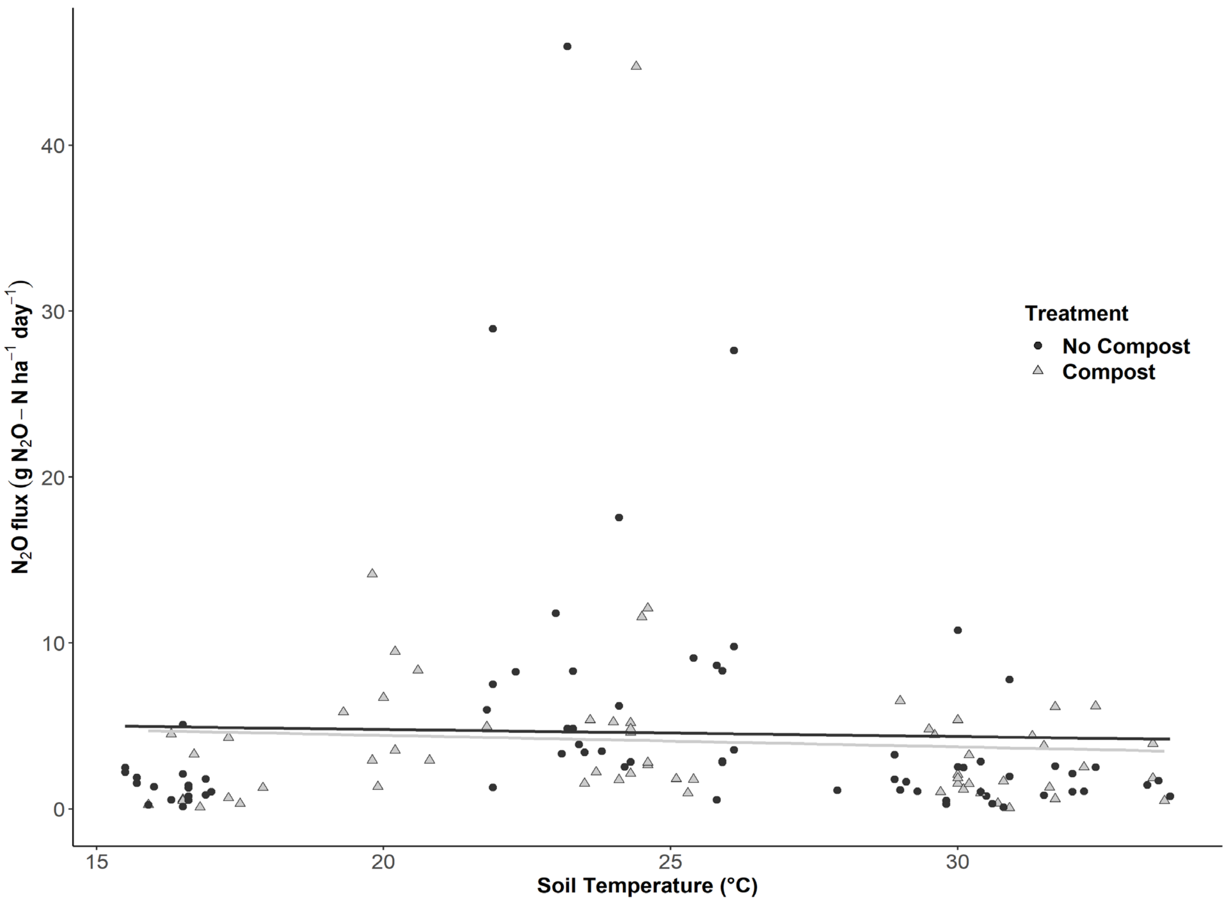
Supplemental Table 3.1. Soil characteristics Student's T-test results.

Soil Characteristic	T-value	Degrees of freedom	P-value	95 % CI for the difference of the means	Mean of the differences
pH (1:1)	1.266	2	0.333	-1.23924 -- 2.27257	0.5166667
EC (1:1)	1.665	2	0.2378	-0.162640 -- 0.367973	0.1026667
Total N (% mg N)	1.7104	2	0.2293	-0.070729 -- 0.164062	0.04666667
Total C (% mg C)	1.9905	2	0.1848	-0.615669 -- 1.675669	0.53
Bulk Density (g cm^{-3})	-3.2088	2	0.08493	-0.0861166 -- 0.0125410	0.03678778

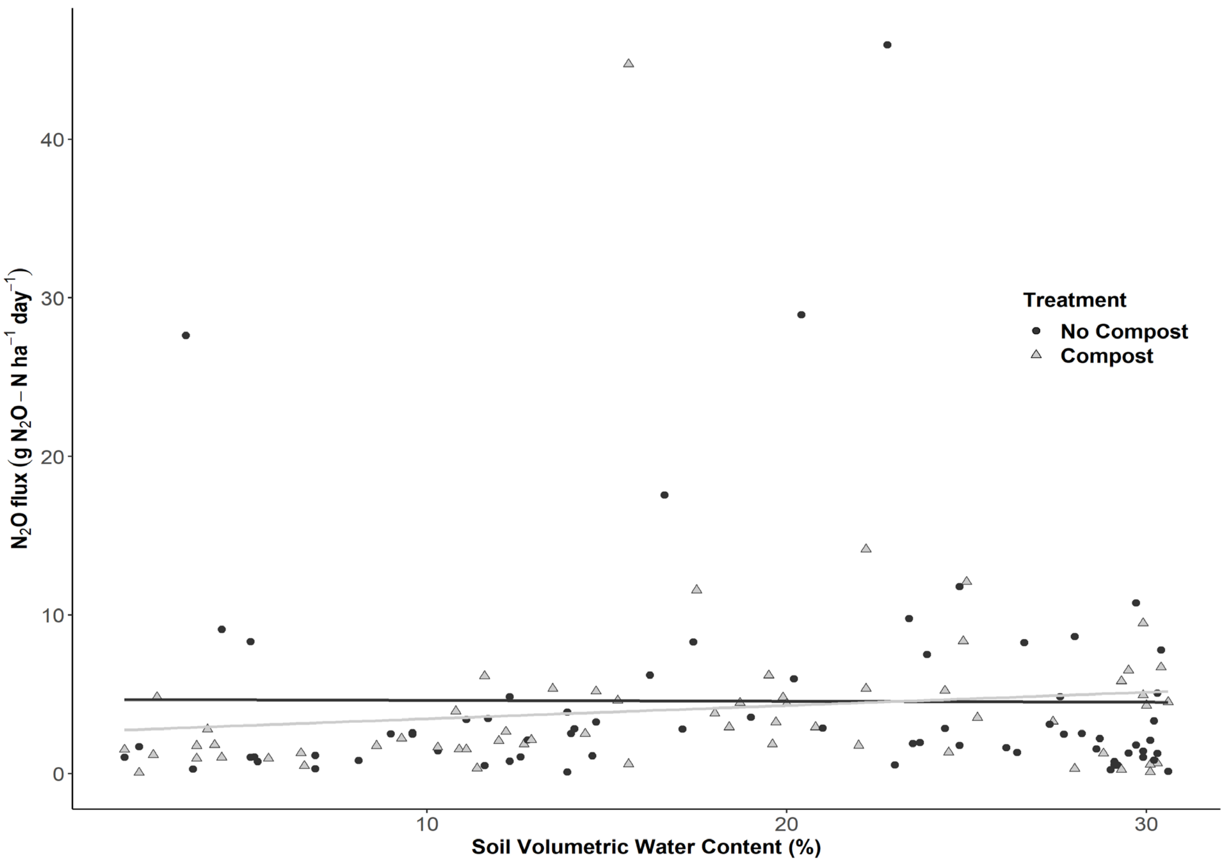
Supplemental Table 3.2. Post-hoc least squares means pairwise contrast of treatments on sampling days

Date	Contrast Estimate	SE	df	t.ratio	p.value
2018-12-17	0.515	0.439	126	1.174	0.2428
2019-03-13	-0.819	0.454	126	-1.803	0.0737
2019-03-21	0.469	0.406	126	1.155	0.2504
2019-04-22	0.155	0.406	126	0.382	0.7028
2019-05-06	0.164	0.456	126	0.361	0.7190
2019-05-23	0.226	0.406	126	0.556	0.5795
2019-06-28	0.328	0.406	126	0.808	0.4207
2019-07-11	1.512	0.423	126	3.574	0.0005
2019-08-07	0.712	0.423	126	1.682	0.0951

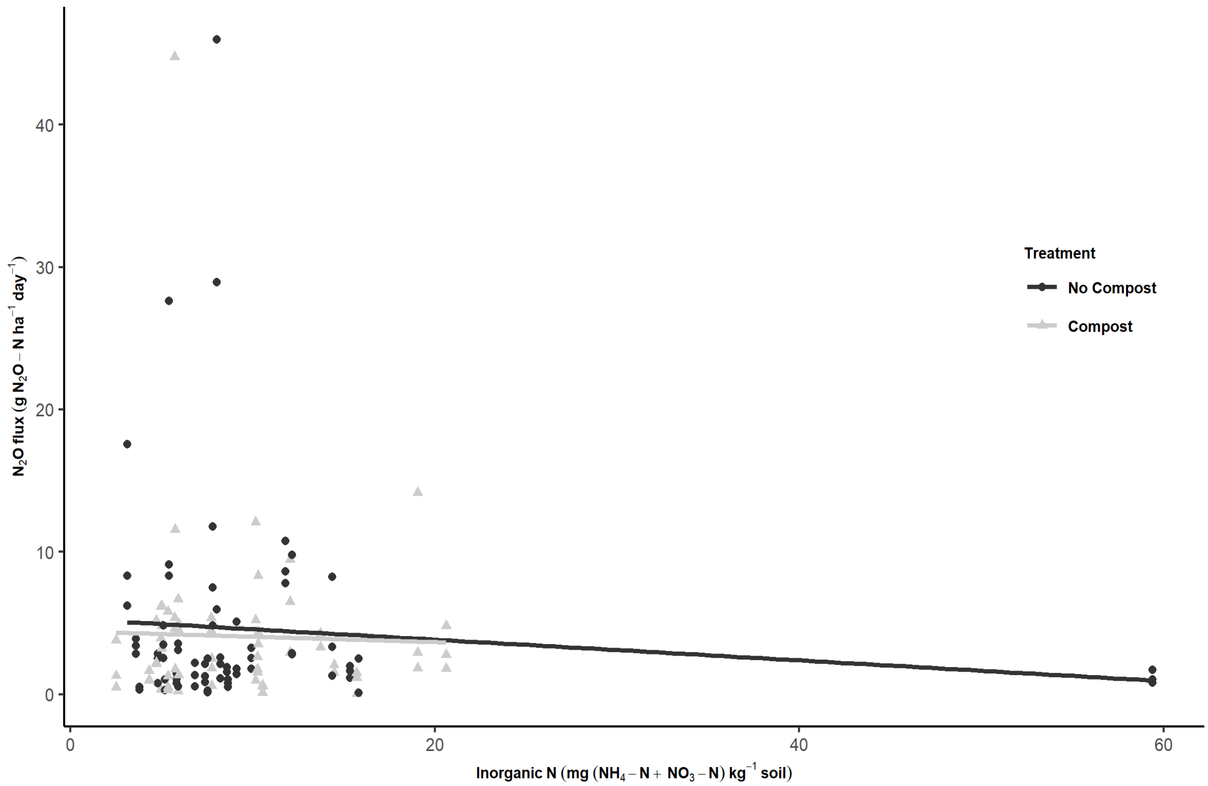
Results are averaged over the levels of: zone
Degrees-of-freedom method: kenward-roger



Supplemental Figure 3.1: Soil temperature measurements during sampling and N_2O fluxes with linear regression, No Compost: R2= 0.001277 , N_2O fluxes = 0.04901 (Temp) + 3.37462; Compost: : R2= 0.01434 , N_2O fluxes = 0.11129 (Temperature) + 6.45712.



Supplemental Figure 3.2: Soil volumetric water content measurements during sampling and N_2O fluxes with linear regression, No Compost: R2= 0.007386 , N_2O fluxes = -0.07194 (Soil Water Content) + 5.85926; Compost: : R2= 0.0317 , N_2O fluxes = 0.09875 (Soil Water Content) + 1.86079.



Supplemental Figure 3.3: Soil inorganic nitrogen concentration during sampling and N_2O fluxes with linear regression, No Compost: R2= 0.0113 , N_2O fluxes = -0.07098 (Inorganic N) + 5.09604; Compost: : R2= 0.0003344 , N_2O fluxes = -0.02209 (Inorganic N) + 4.02722.