Greenhouse Gas Emissions from Pecan Orchards in Semiarid Southern New Mexico

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Abstract. Greenhouse gas (GHG) emissions are fueling global climate change, with methane and nitrous oxide being the primary agricultural gases emitted. It has been shown that N₂O emissions correlate to moisture content fluctuations; however, emissions from agricultural fields in the semiarid regions of the Southwest where rewetting events occur regularly are not well established. The scope of this study was to quantify GHG emissions in correlation to soil moisture fluctuations and fertilizer application. The study was conducted continuously in two pecan [*Carya illinoensis* (Wangenh.) K. Koch] orchards between Aug. 2010 and Aug. 2011 on a sandy loam soil (La Mancha) and a silty clay loam soil (Leyendecker), both under normal management practices. The small chamber technique was used to measure GHGs. Emissions varied greatly throughout the year. The largest flux of CO₂ at La Mancha and Leyendecker both occurred during a drying event immediately following an irrigation event: 84,642.49 $\mu\text{g}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$ and 30,338.24 $\mu\text{g}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$, respectively. The net CH₄ flux at Leyendecker and La Mancha was close to zero with the largest emissions occurring during wetting events. Results showed that N₂O emissions were maintained near the baseline except for the few days following an irrigation event. The largest emission peak at La Mancha occurred after irrigation and nitrogen application: 322.06 $\mu\text{g}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$. The largest emission peaks of 26.37 and 1.13 $\mu\text{g}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$ at Leyendecker and La Mancha, respectively, occurred after irrigation, nitrogen application, and tillage. Nitrogen application was the driving factor affecting N₂O emissions at La Mancha, whereas soil moisture content was the driving factor at Leyendecker. Emission factors (EFs) at La Mancha and Leyendecker were 0.49% and 0.05%, respectively. A thorough accounting of GHG emissions is necessary for budgeting and identifying mitigation policy.

Carbon dioxide, methane (CH₄), and nitrous oxide (N₂O) are major contributors to the increases in GHG emissions, fueling changes in the earth's climate. The USEPA (2015) estimates that GHG emissions due to agriculture accounted for 7.6% of total emissions in 2013, with CH₄ and N₂O being the primary GHGs emitted. Agricultural practices contribute up to 74.4% of US N₂O emissions and enteric fermentation and manure management contribute up to 34.6% of CH₄ emissions (USEPA, 2015). N₂O is 296 times and CH₄ 23 times more effective than CO₂ in causing an immediate increase in global warming. It has been estimated that a 2-fold increase in atmospheric N₂O would result in a 10% decrease in ozone and, therefore, cause a 20% increase in ultraviolet radiation reaching the earth (Crutzen and

Ehhalt, 1977). Even though CO₂ is the main GHG of concern for national and global budgeting, for agriculture, the most important is N₂O (Snyder et al., 2009). Biotic and anthropogenic activities have caused an increase in atmospheric N₂O (Andreae and Schimel, 1989; Rhode, 1990), with N₂O from soils largely accounting for these increases.

Agricultural practices are altering the carbon and nitrogen cycles through combustion of fossil fuels, application of N fertilizers, cultivation of N-fixing legumes, and other actions, with agriculture being the main contributor to N₂O in the atmosphere. N₂O is increasing at a rate of 0.2% to 0.3% a year (Vitousek et al., 1997). In the past, land conversion to croplands caused major perturbations in soil N processes. Continued growth of atmospheric N₂O has been partly attributed to increased N input into the soil system (Mosier et al., 1996). To continue global food production to meet the needs of an expanding population, soil N input is expected to continue over the next 100 years (Hammond, 1990). The Intergovernmental Panel on Climate Change currently recommends an EF (amount of N₂O lost per unit of N applied) of 1.25% of the amount of N applied for the accounting of N₂O emissions from agricultural soils (IPCC, 1997).

Greenhouse gas emission variations found in the literature are due to a variety of factors (Mosier et al., 1996; Smith et al., 2003) including crop, soil texture, temperature (Cates Jr. and Keeney, 1987; Hart, 2006; Johnson et al., 2010; Wagner-Riddle et al., 1994), fertilization and other management techniques (Alluvione et al., 2010; Amos et al., 2005; Dusenbury et al., 2008; Halvorson et al., 2008, 2010; Jacinthe and Dick, 1997; Ma et al., 2010; Mosier et al., 2006), and soil moisture (Adviento-Borbe et al., 2006; Cates Jr. and Keeney, 1987; Hernandez-Ramirez et al., 2008; Rochette et al., 2007; Russow et al., 2007; Welzmler et al., 2008; Zhang et al., 2008). Few studies have been carried out in the semiarid region of the Southwest United States quantifying N₂O emissions as they are related to biological and physical factors.

The amount of N₂O released into the atmosphere is likely underestimated because the effect of N input is only partially traced through the environment and estimates do not include production from animal manure and biological fixation (Mosier et al., 1996). Because of water being limited, we believe that the potential to reduce N₂O emissions is much higher than the potential to increase C sequestration as a GHG mitigation technique in the semiarid southwest than in the high plains and southeast. An array of studies is needed that take into account N₂O emissions as affected by N application, crop, climate, and management technique throughout the year and not just the cropping season, and to create more accurate prediction models on an area, regional, and global scale (Mosier et al., 1996). To the best of our knowledge, no studies have quantified GHG emissions from irrigated pecan orchards of southern New Mexico. The objectives of this research are 1) to examine the effect of soil moisture, fertilization, climate, and soil texture on N₂O emissions, 2) to quantify N₂O, CH₄, and CO₂ emissions throughout the year, and 3) to report percent of N application lost as N₂O for some pecan orchards in semiarid southern New Mexico. The hypothesis for this research is that N₂O emissions are a direct function of moisture content fluctuations and fertilization events.

Materials and Methods

Experimental sites. We established sites at two pecan [*C. illinoensis* (Wangenh.) K. Koch] orchards: New Mexico State University Leyendecker Plant Science Research Center, located 14.5 km south of Las Cruces (lat. 32°11'56.66"N, long. 106°44'30.50"W, and altitude of 1,174 m above sea level), and a private orchard (La Mancha), located 12.7 km northwest of Las Cruces, NM (lat. 32°17'5.32"N, long. 106°50'3.85"W, and altitude of 1,185 m above sea level). Soils at Leyendecker and La Mancha are primarily Arimjo clay loam and Brazito very fine sandy loam, respectively. Soil properties at the sites are referenced in Table 1 (Deb et al., 2013). The climate of the experimental areas is

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Table 1. Soil properties of La Mancha (Site 1) and Leyendecker (Site 2) at Las Cruces, NM. K_s = saturated hydraulic conductivity, FC = water content at field capacity (at 30 kPa), and WP = water content at wilting point (at 1,500 kPa) (Deb et al., 2013).

Soil depth (cm)	Particle size distribution (%)			Bulk density (Mg·m ⁻³)	K _s ^a (cm·min ⁻¹)	FC ^a (cm ³ ·cm ⁻³)	WP ^a (cm ³ ·cm ⁻³)
	Sand	Silt	Clay				
Site 1							
0–20	63.60 ± 0.86*	27.50 ± 0.96	8.90 ± 0.10	1.44 ± 0.02	0.012 ± 0.001	0.27 ± 0.0002	0.06 ± 0.04
20–40	82.10 ± 3.43	13.50 ± 3.18	4.40 ± 0.31	1.36 ± 0.04	0.0311 ± 0.002	0.17 ± 0.03	0.06 ± 0.0
40–60	92.60 ± 2.14	3.50 ± 1.66	3.90 ± 0.49	1.37 ± 0.04	0.064 ± 0.0031	0.15 ± 0.01	0.03 ± 0.01
60–80	94.60 ± 1.97	1.75 ± 1.80	3.65 ± 0.32	1.33 ± 0.07	0.062 ± 0.0024	0.12 ± 0.01	0.03 ± 0.01
Site 2							
0–20	22.84 ± 1.92	51.00 ± 1.47	26.16 ± 0.71	1.53 ± 0.04	0.0001 ± 0.0000	0.35 ± 0.04	0.17 ± 0.003
20–40	10.84 ± 1.29	59.00 ± 1.29	30.16 ± 0.82	1.28 ± 0.05	0.0001 ± 0.0001	0.36 ± 0.02	0.19 ± 0.01
40–60	49.34 ± 12.99	37.25 ± 10.88	13.41 ± 3.59	1.24 ± 0.08	0.0174 ± 0.0108	0.25 ± 0.01	0.11 ± 0.0
60–80	37.84 ± 11.52	51.00 ± 10.74	11.16 ± 2.00	1.11 ± 0.05	0.0097 ± 0.0028	0.26 ± 0.03	0.12 ± 0.01

classified as arid with average annual temperature and precipitation of 17.7 °C and 29.7 cm, respectively (Gile et al., 1981). Both experimental sites are flood irrigated with groundwater and canal water. Both fields were managed under conventional farming techniques using shallow tillage. Fertilizer was applied as broadcast application followed by flood irrigation; La Mancha received three applications of 46–0–0: N–P–K (urea) and Leyendecker two applications of 21–0–0: N–P–K (ammonium sulfate) and 11–52–0: N–P–K (monoammonium phosphate).

Field experiment. We used the closed small chamber method to measure GHG fluxes to quantify point emission rates. The chamber method has been reported to underestimate the actual emission rates because of inherently nonlinear time series data (Venterea et al., 2009). Our chamber design was based on Mosier's (1989) review of key issues related to chamber techniques for flux measurements. The apparatus consisted of two parts, an anchor of 20.32 cm diameter by 5.08 cm length PVC and the chamber of 20.32 cm diameter by 15.24 cm long PVC pipe and a 20.32 cm PVC endcap. Chambers were not left in place for longer than 1 h to prevent an increase of the temperature inside the chamber and to maintain linear regression of the flux.

We took gas samples using four replicates at each site by withdrawing gas from inside the chambers using a 20 mL syringe, 0, 30, and 60 min after the chambers were installed. We stored the samples with an overpressure of air in 12-mL soda glass flat-bottom evacuated vials (LabCo, High Wycombe, UK). The University of California Davis Viticulture and Enology laboratory conducted the GHG analysis using a gas chromatograph (GC-2014; Shimadzu Scientific Instruments, Columbia, MD) equipped with electron capture detector, thermal conductivity detector, and flame ionization detector to quantify N₂O, CO₂, and CH₄, respectively. We collected samples between two and five times a week following fertilizer application and irrigation events to capture the rising and falling limbs of the CO₂, CH₄, and N₂O emission curves accurately. During the rest of the year, we collected samples every 2–3 weeks with additional sampling conducted during periods of change in soil and environmental properties. We conducted sampling between 8 and 10 AM. During sampling events,

Fig. 1. CO₂, CH₄, and N₂O emissions from eight in vitro soil cores. Cores underwent three sequential treatments: field capacity, saturation, and saturation with 168.128 kg·ha⁻¹ urea (N). Cores one to four were collected from each replicate point at La Mancha and five to eight from those at Leyendecker. The vertical bars denote the sd.

we took internal chamber temperature readings at 0, 30, and 60 min; soil temperature readings; and soil samples at each replicate from 10, 20, and 30 cm to determine soil moisture content and nitrate concentration.

Laboratory experiment. We collected four replicate soil cores between 10 and 20 cm from each field to collect in vitro gas samples to study the effect of anaerobic conditions and fertilizer application on GHG emissions. We incubated cores, 5 cm in diameter, in the dark for 7 d at 20 °C in 1-L mason jars with a septa butyl stopper installed in the lid. Incubations took place at field

capacity (Table 1), saturation, and at saturation with a surface fertilizer application (168.13 kg·ha⁻¹ urea), respectively. Cores were initially saturated and then equilibrated to field capacity (–0.3 bar) using a pressure plate apparatus before the first incubation. The second incubation was conducted after re-saturation and the third after granular urea application with wetting. Gas samples were collected at time 0, 1, 3, 24, 72, and 168 h, with atmosphere equilibration at 24 and 72 h. We collected air samples from inside the jars using a 20 mL syringe. The samples were stored with an overpressure of air in 12-mL

soda glass evacuated vials (LabCo) until analyzed.

Data collection. Using the concentrations of CO_2 , CH_4 , and N_2O determined by UC Davis, GHG flux was calculated by linear regression using the equation:

$$F = (V/A)(\Delta c/\Delta t)(p/RT),$$

where F is the GHG flux ($\mu\text{g}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$), V is the volume of air within the chamber (L), A is the area of soil under the chamber (m^2), $\Delta c/\Delta t$ is the rate of change of the N_2O concentration ($\mu\text{L}\cdot\text{L}^{-1}\cdot\text{h}^{-1}$), p is the air pressure (atm), R is the gas constant ($0.08206 \text{ L atm/mol K}$), and T is the mean air temperature (K).

We determined gravimetric soil moisture by weighing soil samples, drying the samples to constant weight at 105°C for 24 h, and reweighing. Water content percentage was calculated using the equation:

$$W\% = [(WS - DS)/(DS - B)] \times 100,$$

where $W\%$ is the percentage of water in the soil. B is the weight of the pan, WS is the weight of the pan and wet soil, and DS is the weight of the pan and the dry soil.

We determined nitrogen content of the soil by extracting the free NO_3^- with 2 M KCl, filtering, and freezing the mixture until analysis. We tested the liquid using an automated spectrophotometric method (Maynard and Karla, 1993).

We calculated annual CO_2 , CH_4 , and N_2O emissions by taking the sum of the average daily flux. We calculated EF of N_2O emissions as the annual emission per the nitrogen applied. This allows for direct comparisons across experimental sites. We calculated EFs without a correction for background flux as the experimental sites were managed under normal management practices and there were no non-fertilized controls.

Results and Discussion

Results from in vitro soil cores showed that CO_2 emissions were highest ($11,400.41 \mu\text{g}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$) under field capacity and CH_4 emissions were highest under saturation ($0.99 \mu\text{g}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$). N_2O emissions from the in vitro soil cores were highest ($115.12 \mu\text{g}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$) under saturation with a nitrogen application (Fig. 1). The average gas flux was higher at La Mancha than at Leyendecker ($P = 0.05$).

Soil moisture content values are plotted along with flux data (Figs. 2 and 3). Soil water content values were consistently higher at Leyendecker than at La Mancha and varied between 8.18% and 31.73% and 8.97% and 21.02%, with an average of 18.82% and 13.53%, respectively, during the growing season. This is mainly because of the differences in soil texture as each site was irrigated at similar intervals.

Looking at Figs. 2 and 3, it is clear that soil NO_3^- varied with rising and falling moisture content as well as fertilizer application. After the first fertigation event of the season soil, NO_3^- went from 7.5 to $45.0 \text{ mg N/kg dry soil}$ and 6.3 to $21.6 \text{ mg N/kg dry soil}$

Fig. 2. CO_2 , CH_4 , and N_2O emissions ($n = 4$) and moisture and NO_3^- content at La Mancha, Sept. 2010–Aug. 2011. Irrigation and irrigation with N application are indicated by black and black arrows with plus signs, respectively. The vertical bars denote the SE.

on days 236 and 219 at Leyendecker and La Mancha, respectively. At Leyendecker, soil NO_3^- was highest a few days after an irrigation event and peaks ranged from 21.3 to $55.3 \text{ mg N/kg dry soil}$ (Fig. 3). At La Mancha, soil NO_3^- was highest immediately following irrigation and peaks ranged from 23.8 to $61.4 \text{ mg N/kg dry soil}$ (Fig. 2).

Linear regression modeling between soil water content and CO_2 or CH_4 emissions did not produce a significant correlation on accord with their wide fluctuations throughout 2010 and 11. The largest flux of CO_2 at La Mancha ($84,642.49 \mu\text{g}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$) and Leyendecker ($30,338.24 \mu\text{g}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$) occurred during a drying event immediately following an irrigation event (Figs. 2 and 3). The net CH_4 flux at Leyendecker and La Mancha was close to zero with the largest emissions occurring during wetting events (Figs. 2 and 3).

N_2O emissions varied greatly throughout the year at each site. They increased immediately

following irrigation events and then declined. The largest emission peak of $322.1 \mu\text{g}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$ at La Mancha occurred after irrigation and nitrogen application (Fig. 2). This supported the hypothesis of this study that N_2O emissions are a direct function of moisture content fluctuations and fertilization events. The largest emission peak of $26.37 \mu\text{g}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$ at Leyendecker occurred after irrigation and tillage (Fig. 3). La Mancha had the highest annual flux of 1.129 kg N/ha and % nitrogen loss (EF) of 0.49% (Table 2).

N_2O emissions were lower from Leyendecker than from La Mancha in both the laboratory and the field (Fig. 1; Table 2), although the difference in the field results ($P = 0.008$) was much more dramatic than that in the laboratory ($P = 0.05$). The lower N_2O emissions were probably a result of low soil mineral N content because of lower N fertilizer rates at Leyendecker; this is in agreement with other studies that N input is more important than other factors as a predictor

Fig. 3. CO₂, CH₄, and N₂O emissions (n = 4) and moisture and NO₃⁻ content at Leyendecker, Sept. 2010–Aug. 2011. Irrigation and irrigation with N application are indicated by black and black arrows with plus signs, respectively. The vertical bars denote the SE.

Table 2. Annual CO₂, CH₄, and N₂O fluxes; fertilizer rates; and emission factors (EFs) at La Mancha and Leyendecker.

Site	Annual CO ₂ emissions (kg C/ha)	Annual CH ₄ emissions (kg C/ha)	Annual N ₂ O emissions (kg N/ha)	Fertilizer application rate (kg N/ha)	EF (%)
Leyendecker	323	0.024	0.036	70.4	0.05
La Mancha	1,114	0.010	1.13	231.8	0.49

of N₂O emissions (Dusenbury et al., 2008; Halvorson et al., 2008; Jacinthe and Dick, 1997; Ma et al., 2010). Higher N₂O emissions at Leyendecker are expected because of its higher clay content and soil bulk density (Table 1) than La Mancha (Linn and Doran, 1984; Rochette et al., 2007).

CO₂ emissions were lower and CH₄ emissions were higher at Leyendecker, where the bulk density was higher despite having a higher percentage of clay content (Table 1) than that at La Mancha. This is consistent with decreased soil respiration and increased

anaerobic conditions reported on compacted soils (Linn and Doran, 1984).

Factors affecting GHG emissions from agricultural soils have been shown to be a function of soil moisture, fertilizer application, other management techniques, temperature, crops, and soil texture (Halvorson et al., 2008; Hargreaves et al., 1994; Jacinthe and Dick, 1997; Mosier et al., 1996; Smith et al., 2003). N₂O emissions are directly related to soil moisture content (Cates Jr. and Keeney, 1987; Dungan et al., 2016; Halvorson et al., 2016; Hernandez-Ramirez

et al., 2008) and exhibit large peaks immediately after the rewetting of dry soils (Davidson, 1992; Leitner et al., 2017). This indicates the importance of observing drying–wetting conditions that occur in irrigated agricultural fields of semiarid regions. N₂O emissions are reliant on both moisture content and soil NO₃⁻; when available NO₃⁻ is not a limiting factor, the relationship between moisture content and EF has been shown to be linear (Dobbie and Smith, 2003). Higher N₂O emissions as moisture content increases and its correlation to increased soil NO₃⁻ suggest that denitrification is the primary source of N₂O emissions. The results from this project support these conclusions. Denitrification as the primary source of N₂O emissions has been confirmed using other techniques (Ostrom et al., 2010; Russow et al., 2007).

Because of any one of the controlling factors becoming limiting, the analysis of flux response to a single variable has proved to be more useful than the use of multiple regression techniques (Dobbie and Smith, 2003). At La Mancha, an exponential relationship was found between soil NO₃⁻ and N₂O flux ($P < 0.09$) (Fig. 4), although results are too weak to provide a direct correlation. At Leyendecker, a significant exponential relationship was found between N₂O flux and $W\%$ ($P < 0.01$) (Fig. 5). Although not always consistent, the results of these relationships support moisture content and N application being key controlling factors for N₂O emissions; these results are consistent with those reported in other studies.

EFs varied widely among the two test sites but were still well below the 1.25% IPCC coefficient factor recommended in calculating N₂O emissions. If the 1.25% coefficient factor was used, annual emissions would be several times higher than those observed: 0.88 kg N/ha and 2.9 kg N/ha, respectively, for Leyendecker and La Mancha. Studies have shown low N₂O emissions in arid regions (Snyder et al., 2009). This study confirms the conclusion of Dusenbury et al. (2008) that a lower loss predictor should be adopted by the IPCC for semiarid regions. A thorough accounting of N₂O emissions is imperative for determining the true mitigation potential of management practices (Gregorich et al., 2005).

Mitigating agricultural N₂O emissions requires the consideration of matching spatial and nutritional needs of crops through limiting and regulating mineral N and water to maximize resource uptake. Possible nitrogen management practices include the following: minimize excess N application, split nitrogen application, precision irrigation application, and application of slow release N sources (Dajal et al., 2003). Improving irrigation efficiency is of particular importance in the semiarid southwest to manage N₂O emissions. These techniques would limit excess mineral N in the soil, reduce the time soil is saturated, and ensure that resources are spatially available to crops.

Fig. 4. Relationships between CO₂, CH₄, and N₂O vs. water content (%W) and N₂O vs. NO₃⁻ at La Mancha.

Fig. 5. Relationships between CO₂, CH₄, and N₂O vs. water content (%W) and N₂O vs. NO₃⁻ at Leyendecker.

Conclusion

In the semiarid region of Southern New Mexico, N₂O emissions were highest from pecan orchards immediately following a fertigation application. The increased N₂O emissions as soil nitrate and moisture content increase suggest that anaerobic denitrification is the dominant mechanism of N₂O production in the field. This study further supports the adoption of a lower coefficient

factor by the IPCC for semiarid regions. Further research on the effect of alternative irrigation techniques after fertilizer application could be beneficial in the future for the reduction of N₂O emissions and to further a thorough emissions accounting system.

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