Determining NO_x Emissions from Soil in California Cropping Systems to Improve Ozone Modeling

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List of Figures

List of Tables

Abstract

Soils are a source of oxides of nitrogen (NO_x = nitric oxide and nitrogen dioxide), precursors for the production of ozone (O_3), an air pollutant in the troposphere. Production of nitric oxide (NO) occurs through soil microbial processes using ammonium from nitrogen fertilizer and manure inputs or soil mineral nitrogen (N). Emissions of NO_x were measured in almond, alfalfa, tomato, wheat, and silage corn cropping systems during summer months to obtain estimates of NO_x emissions that could potentially be used in regional models predicting O_3 in the San Joaquin Valley. The lowest average NO_x fluxes (<0.1 g NO-N ha^{-1} h^{-1}) were measured at low soil moisture and in subsurface drip-irrigated tomato. The highest average emissions (0.5–2.8 g NO-N ha^{-1} h^{-1}) occurred in high N input systems, such as silage corn. In alfalfa, almond, and furrow-irrigated tomato, average NO_x fluxes were intermediate (0.1–0.5 g NO-N ha^{-1} h^{-1}). The NO_x emissions were related to N inputs, time since fertilizer applications, temperature, and soil moisture. Under field conditions NO_x fluxes increased 2.5-3.5-fold for each increase in soil temperature of 10ºC. The NO_x emissions seem predictable in systems receiving N at recommended rates, ranging from 0.02 – 2.5 g NO-N ha^{-1} h^{-1} in alfalfa, wheat, tomato, and almond, but in systems receiving large N inputs resulting in high concentrations of ammonium, episodes of very high NO_x emissions (>40 g NO-N ha^{-1} h^{-1}) that are difficult to predict occur.

Executive Summary

Background

Soils are one of the sources of NO_x (nitric oxide and nitrogen dioxide), which is involved in reactions producing ozone (O_3), a pollutant in the troposphere. In the San Joaquin Valley, ozone (O_3) levels are often elevated during summer months at many locations and knowledge of all major sources of NO_x is essential to regionally predict O_3 dynamics and evaluate the effectiveness of air quality management programs. To date, estimates of NO_x emitted from agricultural soil are not included in the California Emission Inventory Development and Reporting System (CEIDARS). Soil-borne production of NO_x occurs through soil microbial processes using ammonium from synthetic fertilizer and manure, and soil mineral nitrogen (N). The present study provides estimates of NO_x emissions during summer months from five cropping systems, comprising 17 different locations and management treatments.

Methods

The NO_x emissions were measured in an almond orchard, and in alfalfa, tomato, wheat, and silage corn cropping systems following irrigation and nitrogen fertilization events mostly during June to September in 2011 and 2012. In the almond orchard, microjet sprinklers were used for irrigation and fertigation. Alfalfa and silage corn were flood irrigated. In the silage corn systems, synthetic fertilizer was applied before planting or as a side-dress and with most irrigations, liquid manure was mixed with the irrigation water. Tomato was either furrow-irrigated and most nitrogen fertilizer was applied as side-dress, or subsurface drip-irrigated and fertigated. Wheat, being a rainfed crop receiving N fertilizer in winter, was maturing at the time of the measurements. The NO_x-flux measurements were made by placing a chamber connected to a NO_x-analyzer on the soil surface for 3-5 minutes. The headspace air in the chamber was constantly circulated through the NO_x analyzer, and readings of the concentration of NO_x were taken every 15 seconds. The flux was calculated on a per area basis by taking the rate of change of NO_x concentration, chamber volume and temperature into account. Soil moisture, soil ammonium and temperature were also measured to characterize how environmental conditions and management affected N_2O emissions.

Results

The average hourly NO_x-fluxes were lowest (<0.1 g NO_x-N ha^{-1} h^{-1}) in dry soil, such as maturing wheat and a tractor row in an almond orchard, and under subsurface drip irrigation in tomato. Intermediate fluxes (0.1-0.5 g NO_x-N ha^{-1} h^{-1}) comparable to NO_x emissions reported in earlier studies were observed in almond, alfalfa, and in furrow-irrigated tomato fertilized at recommended N rates. The highest average hourly NO_x fluxes (0.4-2.8 g NO_x-N ha^{-1} h^{-1}) took place in the systems receiving high N inputs, such as dairy silage corn and furrow-irrigated tomatoes fertilized at an excessive N rate. The emissions were related to N inputs leading to high soil ammonium concentrations. On some occasions the magnitude of NOx emissions, which closely followed large N inputs of synthetic N fertilizer and/or liquid dairy manure, matched those of the highest fluxes ever measured. The NO_x fluxes decreased with time since N fertilization. Within a given day, NO_x fluxes increased 2.5-3.5-fold for each increase in soil temperature of 10ºC. The NO_x fluxes were also dependent on soil water content with the highest fluxes occurring at intermediate soil moisture values (30-60% water-filled pore space) and lower fluxes at higher water content.

Conclusions

The emissions at each location varied over time, depending on soil moisture, temperature, and time since N fertilization. The results suggest that NO_x emissions are related to ammonium availability and nitrification rates. Enhanced NO_x fluxes occurred under intermediate soil water contents (water-filled pore space 30-60%), whereas in relatively dry soils or at high water content, NO_x-fluxes were low. Field experiments showed that NO_x emissions increase on average 2.5- and 3.5-fold with each increase of 10°C in soil temperature at 1 and 5 cm depth, respectively. The study showed that NO_x fluxes are fairly predictable in cropping systems fertilized at recommended N rates ranging from 0.02 – 2.5 g NO-N ha^{-1} h^{-1} in alfalfa, wheat, tomato, and almond. However, in the systems receiving high N inputs, such as silage corn, the emissions following N additions resulting in high soil ammonium concentrations can be enhanced by an order of magnitude, reaching hourly fluxes up to 40 g NO-N ha^{-1} h^{-1} for several days. The magnitude and duration of enhanced NO_x emissions (increased by an order of magnitude or more) are not necessarily predictable because they are event-based (e.g. date of N fertilization) and depend on complex interactions among NO production, gas transport and NO consumption in the soil.

Introduction

Measurements of NO_x (nitric oxide NO and nitrogen dioxide NO_2) emissions from agricultural soil in the Central Valley, where ozone (O_3) levels are often elevated during summer months at many locations, are needed as inputs in air quality models. Oxides of nitrogen (NO_x) are directly required for O_3 formation. The build-up of O_3 depends on the ratio of VOC to NO_x, and the influence of these precursors on O_3 production varies temporally and spatially across the landscape (Blanchard and Fairley, 2001). When the ratio of VOCs to NO_x is low, the availability of VOCs limits O_3 formation. However, when the ratio of VOCs to NO_x is high, the availability of NO_x controls O_3 formation, and under these conditions, reducing NO_x will decrease O_3 production while reducing VOCs has little effect on O_3 formation. Therefore, quantifying all major NO_x sources is essential to regionally predict the dynamics of O_3 in the troposphere and evaluate the effectiveness of air quality management programs.

About 16% of the world's annual NO_x emissions originate from microbial activity in soils (Olivier *et al.*, 1998). Agricultural soils and associated fertilizer management are known to be sources of NO_x (Williams *et al.*, 1995). However, only few data of NO_x emissions from California agricultural soils have been reported (Matson and Firestone, 1995; Venterea and Rolston, 2000b; Lee *et al.*, 2009). Estimates of NO_x emissions from biogenic (non-anthropogenic) and fertilizer applications are conspicuously absent in the California Emission Inventory Development and Reporting System (CEIDARS), and this lack of information restricts CARB's ability to develop accurate O_3 prediction estimates through modeling.

The objectives of the present study were to determine NO_x emissions in cropping systems typical for this region and to characterize NO_x flux in response to various amounts of N fertilizer inputs under varying soil and air temperature conditions. This research benefits the State agencies CARB and the San Joaquin Valley Air Pollution Control District by providing needed data to improve models predicting O_3 production.

2. Materials and Methods

2.1. *Field sites description*

This project assessed the NO_x emissions in five different cropping systems including tomato, wheat, alfalfa, corn and almonds. Measurements of NO_x fluxes in the different systems were carried out at sites selected for N_2O emission monitoring in other projects commissioned by CARB ("Assessment of Baseline N_2O Emissions in California Cropping Systems" and "Assessment of Baseline Nitrous Oxide Emissions in California's Dairy Systems, with Dr. Horwath as the PI). The different experimental sites were chosen so that a wide range of management strategies are represented such as different fertilizer inputs (inorganic N, manures), and irrigation systems (furrow, flood and sprinkler irrigation).

2.1.1. *Almond*

The NO_x emissions in almond production systems were assessed in the Nickels Soil Laboratory in Colusa County, CA. Soil at this site is classified as a Fine-loamy, mixed, superactive, thermic Typic Haploxeralf with slightly acidic pH (Table 1). The trees were fertilized with 50 kg N ha^{-1} as UAN32 four times during summer 2011 and 2012. The NO_x flux was measured following fertigation events in the tree rows where water and fertilizer solution were applied through microject sprinklers and in the tractor rows, which were neither irrigated nor fertigated. The tractor row measurements thus served as control. Sampling was carried out at 3 locations both in the tree and tractor rows (n=3).

Table 1. Soil (0-25 cm) characteristics at the almond site in Colusa County, CA (http://casoilresource.lawr.ucdavis.edu/drupal/).

Sand (%)	66.8
Silt (%)	19.2
Clay (%)	14
pH (H_2O 1:1)	6.7
Bulk density (g cm^{-3})	1.62
Organic Matter (%)	0.75
Total N (g kg^{-1})	nd

2.1.2. *Alfalfa*

Two adjacent grower fields in the vicinity of Winters, CA, were used to measure NO_x fluxes from alfalfa. The soil at this site is classified as a Myers clay, which is a fine, montmorillonitic, thermic Entic Chromoxerert (Table 2). One of the fields was a one year-old stand, the other a 5 year-old stand. Fields were flood irrigated approximately every 30 days. No N fertilizers were supplied. Alfalfa was harvested 6 times in 2011. Sampling was carried out on 8 dates, including immediately following a flood irrigation event, as well as on days when the fields were relatively dry. Measurements were made at six locations within each field (n=6).

Table 2. Soil (0-30 cm) characteristics of the alfalfa fields near Winters, CA.

Sand (%)	23
Silt (%)	43
Clay (%)	34
pH (H_2O 1:1)	7.7
Bulk density 5-15 cm (g cm^{-3})	1.43
Total C (g kg^{-1})	12.58
Total N (g kg^{-1})	1.15

2.1.3. *Tomato*

Measurements in tomato systems were conducted at the UC Davis Russell Ranch Sustainable Agriculture research site. Soils at this site are classified as Yolo silt loam, a fine-silty, mixed, non-acid, thermic Typic Xerorthent and Rincon silty clay loam, a fine monmorillonitic, thermic Typic Haploxeralf (Table 3). The NO_x fluxes were measured in the tomato beds at several dates between May and August in furrow- and subsurface drip-irrigated systems. In the furrow-irrigated systems, the NO_x fluxes were assessed at three levels of N fertilization, i.e. 0, 162, and 300 kg N ha^{-1} in a conventional, winter-fallow tomato-wheat rotation, and additionally, a winter cover cropped (oats-vetch-bell beans mixture) system fertilized with 162 kg N ha^{-1}. Fifty kg N were applied on April 12, 2011, as NPK-15-15-15 starter fertilizer (8.7% NH_4^+, 6.3% NO_3^-) in granular form banded at a depth of about 16 cm. The remainder of the N applications were applied as side dress N in the form of urea ammonium nitrate (UAN32), banded on May 13, three weeks after planting, at a depth of 17 cm. Furthermore, NO_x fluxes were measured in subsurface drip-irrigated (SDI) tomato systems in two treatments. One was a winter-fallow and the other a cover-cropped system as above. Both systems were fertilized with a total of 179 kg N ha^{-1}. The starter application was the same as in the furrow-irrigated systems, but the remainder of the N fertilizer was applied as UAN32 as fertigations of 22-33 kg N ha^{-1} between May 19 and July 15, 2011. All treatments were replicated 3 times (n=3).

Table 3. Soil characteristics (0-30 cm) of the tomato cropping system at the UC Davis Russell Ranch Sustainable Agriculture facility.

Sand (%)	21.83
Silt (%)	47.00
Clay (%)	31.17
pH (H_2O 1:1)	6.80
Bulk density beds 5-15 cm (Mg m^{-3})	1.37
furrows	1.52
Organic C (g kg^{-1})	10.30
Organic N (g kg^{-1})	1.00

2.1.4 *Wheat*

Assessment of NO_x flux from wheat systems was carried out in a commercial grower field near Dixon, CA. The soil in this field is classified as a silty clay loam thermic Typic Chromoxerert, its main physical characteristics are summarized in Table 4. The NO_x flux was measured in beds and furrows in three treatments at the end of May in three treatments: 0, 210 kg N applied either as ammonium sulfate and urea or as anhydrous ammonia and urea (112 kg N as starter in early November, and 98 kg N as aerial application in February). In addition to winter rainfall, the field received irrigation from April 16-22. The NO_x flux was also measured in a wheat field at the Russell Ranch Sustainable Agriculture research site (see Table 1 for main physicochemical characteristics). Flux measurements from the Dixon field were collected in 2011 while the measurements at the Russell Ranch were made in 2012. At the Russell Ranch, 112 kg N was applied in the form of urea as starter, and 80 kg was added as foliar N application in early March. In both fields NO_x flux was assessed in beds and furrows, and values were weighted according to area (70% bed, 30% furrow) to calculate average field emissions. Two replications were used per treatment (n=2).

Table 4. Main soil characteristics (0-30 cm) at the wheat field located near Dixon, CA.

Sand (%)	21.3
Silt (%)	43.7
Clay (%)	35
pH (H_2O 1:1)	7.4
Bulk density 5-15 cm (Mg m^{-3})	1.29
Total C (g kg^{-1})	14.9
Total N (g kg^{-1})	1.3

2.1.5. *Dairy silage corn*

Assessment of NO_x flux in corn systems was carried out in three forage production systems surrounding dairy farms, located in the counties of Stanislaus (Farms A and B) and

Sacramento (Farm C). It is characteristic of the dairy farms from the Central Valley in California to use the farmland surrounding the facilities to produce silage corn and other forage crops which are in part fertilized with the manure generated at the dairy farms. Forage cropland land typically receives high annual inputs of nitrogen (N) compared to other cropping systems. According to our previous research, the N inputs into these silage corn/winter forage cropping systems range from 500 to 1200 kg N ha^{-1} yr^{-1}, versus 350 to 600 kg N ha^{-1} yr^{-1} removed in the harvested crop (Geisseler *et al.*, 2012). Manure generated at the farms is either collected as solids from the stables and applied to the fields or flushed with water and stored in anaerobic ponds. The liquid effluent is processed before storage in the lagoons to separate particles larger than a few millimeters from the liquid components. Manure is generally applied as liquid ("lagoon water") and mixed with the irrigation water, although fields may also receive the different forms of solid manure. Liquid manure with high concentrations of NH_4^+ is diluted with irrigation water. In addition, inorganic N fertilizers are added. Irrigation is carried out through flooding of the fields. Monitoring of the NO_x fluxes was carried out before and after the irrigation events at four locations within each field (n=4).

Table 5. Soil (0-30 cm) characteristics of the silage corn systems.

	Farm A		Farm B		Farm C
	Field 1	*Field 2*	*Field 1*	*Field 2*	
Sand (%)	78	70	84	84	31
Silt (%)	16	23	12	10	28
Clay (%)	7	7	4	6	41
pH (H_2O 1:1)	6.7	7.2	6.8	7.3	7.47
Bulk density 5-15 cm (Mg m^{-3})	1.67	1.43	1.37	1.44	1.51
Total C (g kg^{-1})	10.4	12.5	11.8	6.8	12.4
Total N (g kg^{-1})	1	1.2	1.1	0.6	1.3

Table 6. Dairy silage corn nitrogen inputs and application mode.

Year	Dates		N inputs					
	Planting	Harvest	Synthetic Fertilizer-N		Manure- N			Total available N per fertigation event (kg N ha^{-1})
			kg N ha^{-1}	Application	Available (kg N ha^{-1})	Recalcitrant (kg N ha^{-1})	Application	
Farm A								
2011	15 April	22 August	298	Irrigation water	198	69	Irrigation water	20-40
2012	6 May	24 August	182	Irrigation water	172	114	Irrigation water	20-40
Farm B								
2011	15 May	31 August.	104	Injected	245	713	Solid & irrigation water	20-50
2012	13 May	3 September	118	Injected	268	72	Irrigation water	20-50
Farm C								
2011	20 June	14 October	224	Injected	159	35	Irrigation water	159
2012	18 June	21 October	224	Injected	460	100	Irrigation water	89-115

At Farm A, two fields characterized as a coarse-loamy, mixed, active, thermic Typic Haploxeralf with neutral to slightly acidic pH, a total soil C content in the topsoil of 10.4 and 12.5 g kg^{-1} soil, and a high sand content (70-78%)(Table 5). Fertilizer inputs consisted mainly of lagoon water and inorganic N fertilizer (UAN32) applied via the irrigation water (20-40 kg available N ha^{-1} per irrigation event). The total N inputs are summarized in Table 6.

The soil in Farm B was classified as a mixed, thermic Typic Xeropsamment. It was characterized by a high sand content (84%), a neutral to acidic pH, and a total C content in the topsoil of 11.8 g kg^{-1}soil. Solid corral manure, partially composted, and the solid fraction, so called 'separator manure,' remaining after mechanical separation of the liquid manure were incorporated into the soil in spring 2011 after disking and two weeks before corn planting. Synthetic N fertilizer as UAN was applied in early June at the rate of 104 and 117 kg N ha^{-1} in 2011 and 2012, respectively. In addition, lagoon water was mixed into the irrigation water (approx. mixing rate 3:1 fresh water: lagoon water) resulting in N applications of 20-50 kg available N ha^{-1} per irrigation event.

Soil at Farm C was classified as a fine, mixed, superactive, thermic Abruptic Durixeralf. It was characterized by a neutral pH (7.47), a total soil C in the topsoil of 12.4 g kg^{-1}, and a lower sand and higher clay content than on Farms A and B. The main N inputs to the corn crop consisted on 227 kg ha^{-1} of anhydrous ammonia injected in the soil one week before planting, and the application of lagoon water through irrigation (mixing rate 1:1 water: lagoon water), on August 29, 2011 (159 kg available N ha^{-1}) and September 12 and 27, 2012 (115 and 89 kg available N ha^{-1}).

2.2. *NO_x flux measurements*

The NO_x flux took place during the summer months (2011 and 2012) when O_3 reaches critical threshold values, and measurements focused on soil fertilization events (if applicable, e.g. alfalfa is typically not fertilized) and varied soil moisture conditions.

Nitric oxide flux was measured in the field by using a dynamic chamber method. Either rectangular or circular chambers were used depending on the cropping system. Rectangular stainless steel chamber bases were 50 x 30 cm and 8 cm deep with a 2 cm-wide horizontal flange at the top end. Chamber bases were inserted in the soil so that the flanges rested in the soil surface and were left in place unless field operations required their temporal removal. Thin-wall stainless steel (20 gauge) chamber tops (50 x 30 x 10 cm), with flanges facing down and lined with a rubber gasket, were placed onto the bases and secured with metal clamps. Round, 20 cm diameter 10 cm tall polyvinyl chloride (PVC) chambers were used in wheat, alfalfa, and almond systems. Chambers were placed on PVC rings buried 6-8 cm deep into the soil and sealed with a rubber gasket.

Both rectangular and round chambers were equipped with inlet and outlet ports connected to a chemoluminiscence NO_x analyzer (LMA-3, Scintrex/Unisearch Associates, Concord, ON, Canada) via Teflon^{TM} (PTFE) tubing covered by a layer of opaque material to prevent exposure of the air stream to sunlight. Chamber air was continuously circulated by a pump in the NO_x analyzer, flowing through a chromium tri-oxide (CrO_3) column converting NO to NO_2 and then the luminol chemiluminescence detector. NO_x flux was recorded every 15 seconds during 5 minutes right after sealing the chamber. The instrument was calibrated in the laboratory before every field measurement event by mixing NO-free air scrubbed of NO_x

by permanganate-coated porous silica and a NO_x gas standard (Scott Marrin, Inc., Riverside, CA) in varied proportions and at known flow rates (Manostat). Upon return to the laboratory after field measurements, the calibration was checked. On most days, values stayed within 10% of the calibration values. On some days, when re-check values diverged from the calibrated ones obtained in the morning, the results were adjusted to a new calibration curve, representing a mean value of before- and after-field measurements. On a few days, field measurement values were discarded due to instrument problems.

The NO_x flux was calculated from the rate of change in chamber concentration, chamber volume, and soil surface area. Chamber gas concentrations determined by the NO_x-analyzer (volumetric parts per billion) were converted to mass per volume units assuming ideal gas relations using chamber air temperature values, which were measured by a thermocouple thermometer during each sampling event.

2.3. *Effects of environmental variables on NO_x flux*

2.3.1. *Soil chemical and physical analyses*

In order to gain a better understanding of the conditions affecting NO_x emissions, key soil and environmental variables were recorded in addition to the main management practices and N inputs at each site. Inorganic N (NO_3^- and NH_4^+) content was determined in the 0-15 cm soil layer. Soil samples were collected close to the gas chamber bases by using a 1.83-cm steel corer. Soil samples were immediately extracted with 1 M potassium chloride (KCl) at a 1:5 ratio (soil: extracting solution) and analyzed within one day for nitrite (NO_2^-). Extracts were also analyzed colorimetrically for ammonium (NH_4^+) and nitrate (NO_3^-) by a Shimadzu spectrophotometer (Model UV-Mini 1240). For determining NH_4^+, the phenate (indophenol blue) method was employed (Forster, 1995). Nitrate in the extracts was reduced to nitrite (NO_2^-) with vanadium chloride, and the NO_2^- was analyzed by diazotizing with sulfanilamide followed by coupling with N-(1-naphthyl) ethylenediamine-dihydrochloride (Doane and Horwáth, 2003). The pH was determined in the supernatant of soil slurries with H2O by a pH meter (Model 220, Denver Instrument Co., Arvada, CO).

Gravimetric soil moisture was calculated from field-moist and oven-dry (105ºC, 24h) mass of soil collected in the field. Soil texture was determined by a modified pipet method (USDA, 1992). The bulk density was measured twice per growing and rainy season by collecting 10 cm dia. x 6 cm long cores in the 5-15 cm layer of soil, followed by drying the cores to 105ºC. Water filled pore space (WFPS) was calculated from the gravimetric moisture (w) and measured bulk density values in the 5-15 cm layer as follows:

$$\%WFPS = (w * \text{bulk density}) / [1 - (\text{bulk density}/2.65)] * 100\%$$

2.3.2 *Air and soil temperature*

Air and soil temperature at 1 and 5 cm depth were routinely recorded simultaneously with NO_x flux determinations at each individual sampling location. In addition, the relationship between soil temperature and NO_x flux was explored at several field sites by taking measurements of NO_x flux and temperature over the entire course of some days. One of the sites was a sandy loam soil planted to corn and fertilized with 180 kg N ha^{-1} in the form of UAN32 near the UC Davis campus. The other sites were the field locations at Farm B and C. Q10 values were calculated as

$$Q10 = (NO_x\text{-flux}_2/NO_x\text{-flux}_1)^{10/(T2-T1)}$$

where T1 is the temperature in (°C) at 1 or 5 cm depth during NO_x-flux measurement 1 and T2 the corresponding temperature measurement at NO_x-flux measurement 2.

More precisely, soil temperature at 1 and 5 cm depth, and ambient air temperature were recorded simultaneously with NO_x flux determinations at each individual sampling location.

Results

A summary of average hourly NO_x fluxes among all the measurements taken in the different systems is shown in Table 7. The fluxes and results of the ancillary data are explained in detail below and in the accompanying figures.

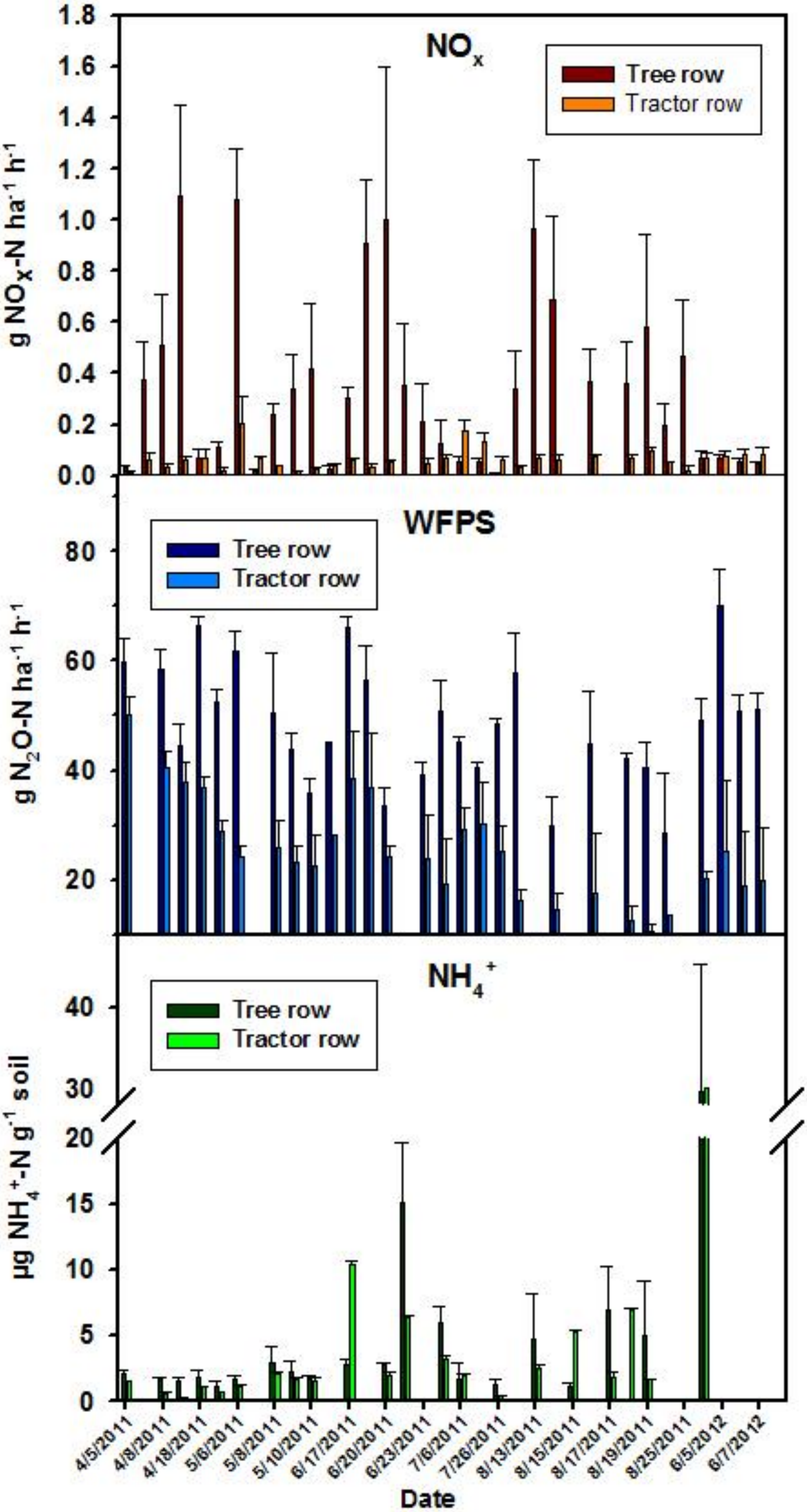
3.1. *Almonds*

The NO_x-flux was higher in the irrigated, fertigated tree than the tractor rows, which remain dry all summer. Following the monthly N fertilizer applications, the NO_x flux reached about 1 g NO-N ha^{-1} h^{-1} and then gradually declined over the course of about 10 d to <0.1 g NO_x-N ha^{-1} h^{-1} (Figure 1). Baseline NO_x emissions in tractor rows were almost always <0.1 g NO_x-N ha^{-1} h^{-1}. In the tree rows, there was a weak correlation of NO_x-flux with nitrite (NO_2^-) (Figure 2). The soil NH_4^+ concentrations did not fluctuate much with the N fertilizer application and were similar in magnitude in the tree and tractor rows. The tractor rows had lower soil moisture content and higher soil temperatures than the tree rows.

Table 7. Summary of mean hourly NO_x fluxes in different cropping systems.

	Avgerage flux	SE
	g NO-N ha^{-1} h^{-1}	
Wheat	0.04	0.01
Alfalfa, 5 year old stand	0.19	0.02
1 year old stand	0.54	0.31
Almond, tractor row	0.06	0.01
Tree row	0.35	0.05
Tomato, SDI winter-fallow (179 kg N ha^{-1})	0.07	0.01
SDI, winter cc (179 kg N ha^{-1})	0.18	0.02
FI, zero N applied	0.10	0.03
FI, standard N rate (162 kg ha^{-1})	0.22	0.05
FI, standard N rate, cc	0.32	0.15
FI, 300 kg N ha^{-1} applied	2.79	0.64
Silage corn, Farm A, Field 1	0.75	0.04
Farm A, Field 2	0.39	0.06
Farm B, Field 1	2.03	0.28
Farm B, Field 2	1.98	0.49
Farm C	2.43	0.55

SDI = Subsurface drip-irrigation; FI = Furrow irrigation; cc = cover crop



NO$_x$
Tree row
Tractor row
g NO$_x$-N ha^{-1} h^{-1}
WFPS
g N$_2$O-N ha^{-1} h^{-1}
NH$_4^+$
µg NH$_4^+$-N g^{-1} soil
4/5/2011
4/8/2011
4/18/2011
5/6/2011
5/8/2011
5/10/2011
6/17/2011
6/20/2011
6/23/2011
7/6/2011
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Date

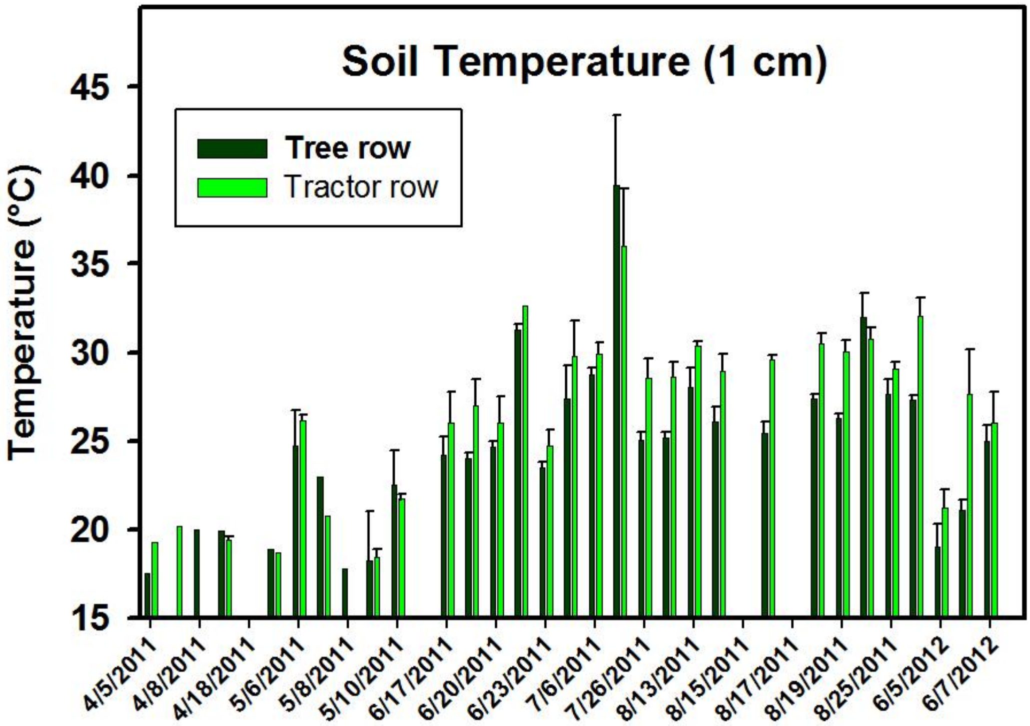


Figure 1. NOx flux, water-filled pores space (WFPS), ammonium (NH_4^+) concentrations, and soil temperature at 1 cm depth in the almond orchard. Standard errors shown as line bars. n=3.

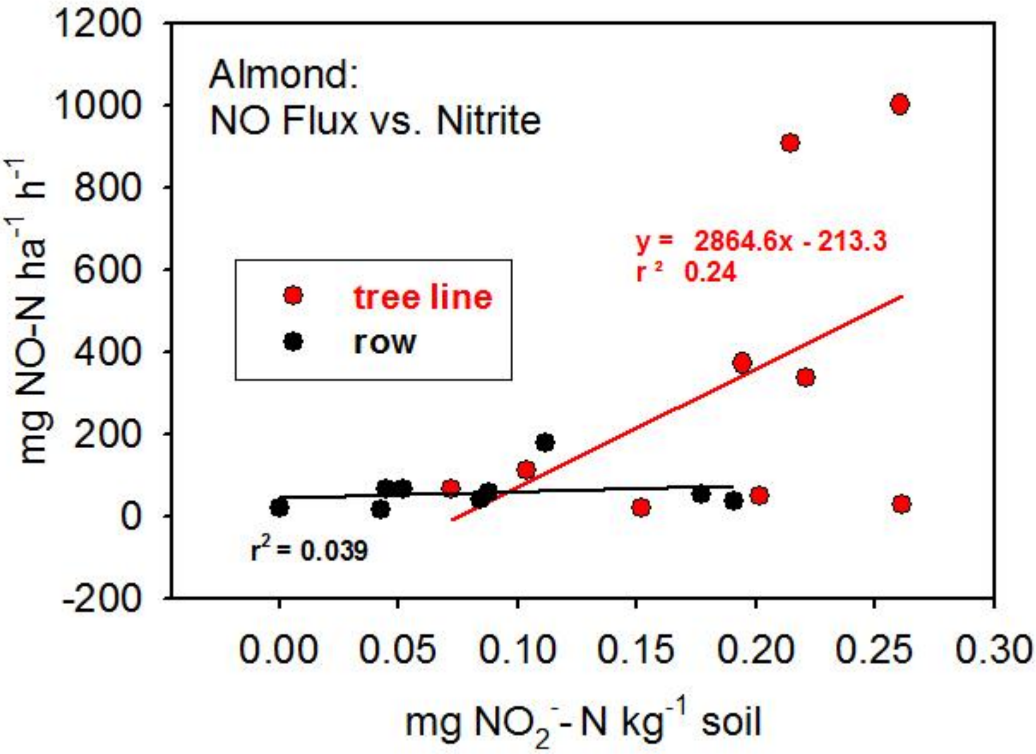
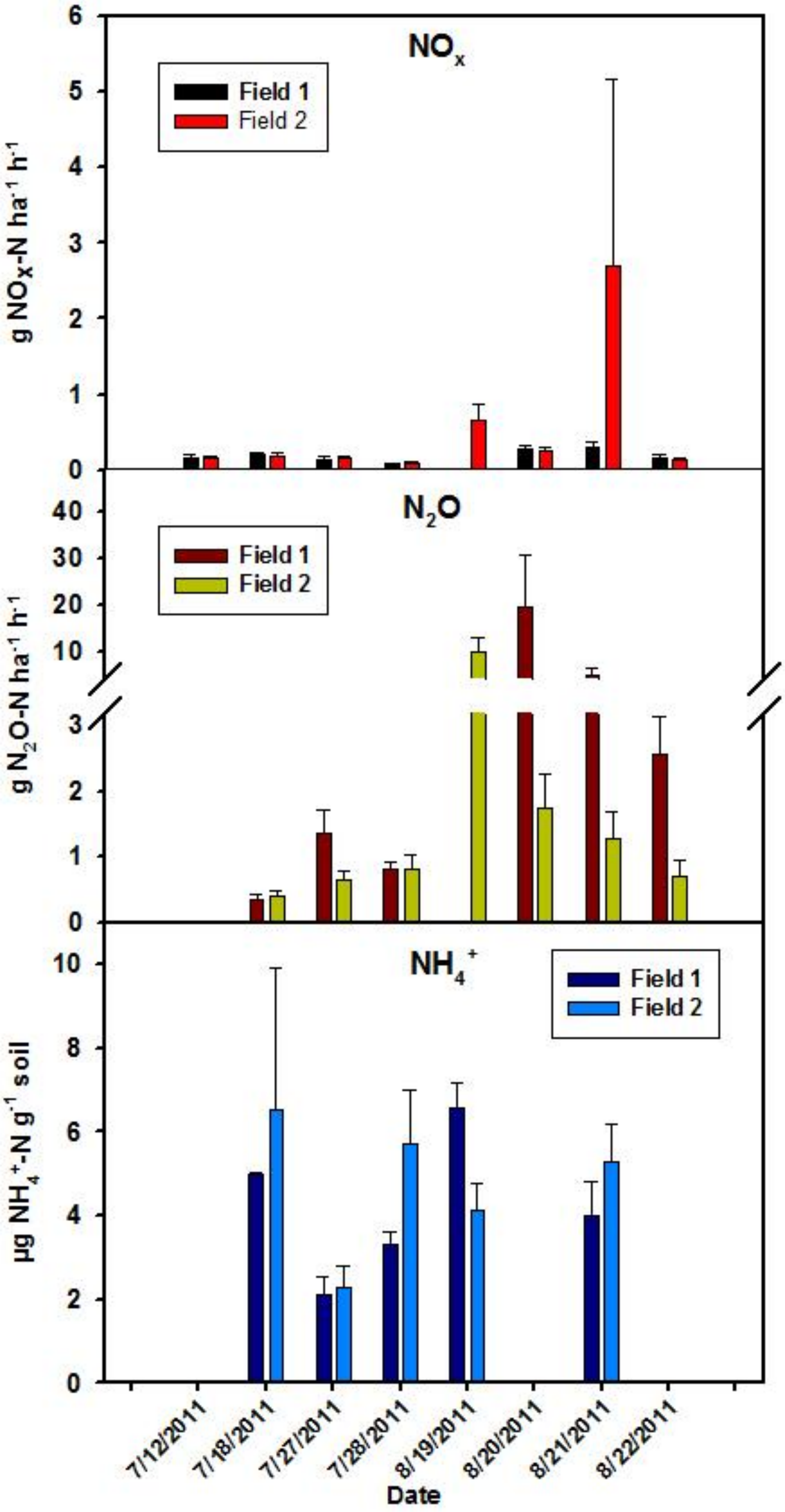


Figure 2. NOx flux vs. nitrite (NO_2^-) concentrations in the soil in the almond orchard.

3.2. *Alfalfa*

In flood-irrigated alfalfa, the NO_x fluxes were generally <0.3 g NO_x-N ha^{-1} h^{-1} except for one event following an irrigation application when the NO_x flux reached almost 3 g NO_x-N ha^{-1} h^{-1} (Figure 3). This enhanced NO_x flux occurred in the 1 year-old field two days after an irrigation event. At this event, the N_2O was greater than the NO_x flux



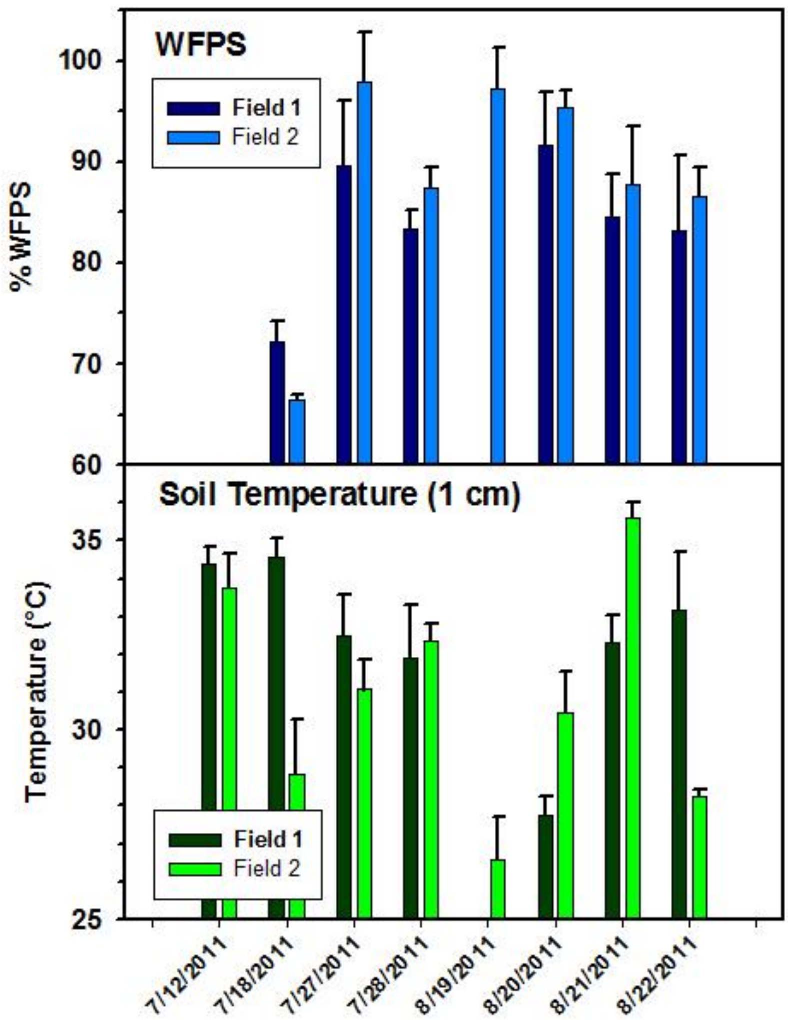
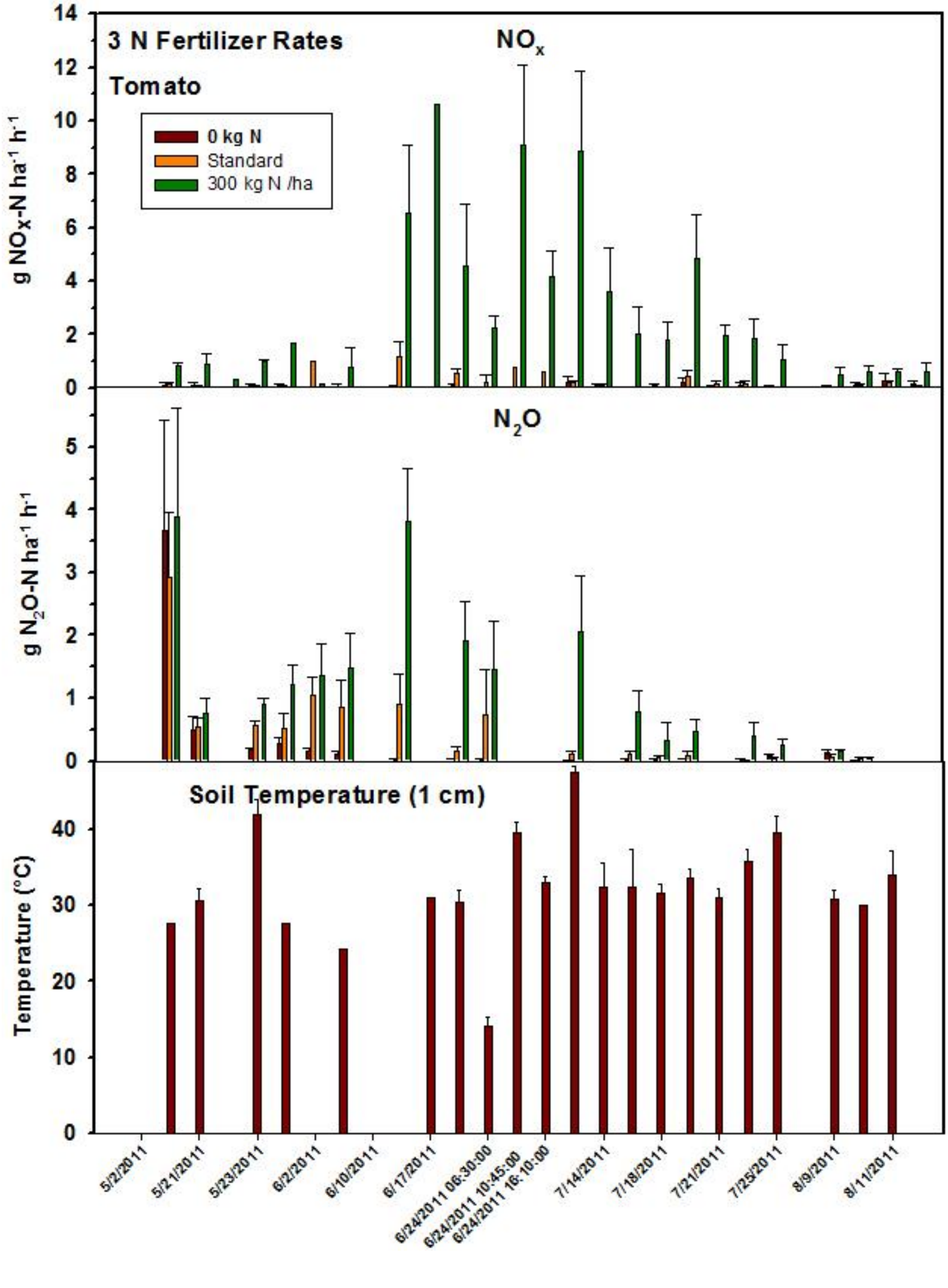


Figure 3. NO_x and nitrous oxide (N_2O) flux, soil ammonium (NH_4^+) concentrations, water-filled pores space (WFPS), and soil temperature at 1 cm depth in the alfalfa fields. Standard errors shown as line bars. n=6.

by an order of magnitude. In both fields soil NH_4^+ concentrations were 2-6 μg NH_4^+-N g^{-1}. The soils almost reached saturation (100% WFPS) after irrigations and declined to 60-70% WFPS in between irrigations. Soil temperatures were lowest immediately following an irrigation and increased with drainage.

3.3. *Tomato*

The NO_x flux ranged from 1-10 g NO-N ha^{-1} h^{-1} in the tomato system fertilized with 300 kg N ha^{-1} (high N treatment), <1 g NO-N ha^{-1} h^{-1} in the system fertilized at the rate of 162 kg N ha^{-1} (standard N treatment), and <0.1 g NO-N ha^{-1} h^{-1} in the plots that did not receive any N fertilizer (zero N treatment) in that season (Figure 4). Most measurements were taken at temperatures (soil temperature at 1 cm depth) around 30ºC. On June 24, 2011, at 6:30 am, the soil temperature was 14.1ºC, increasing to 39.6ºC by 10:45 am, and declining to 33.0ºC by 4 pm. Concurrently, NO_x flux in the high N treatment increased from 2.3 to 9.1, and decreased to 4.2 g NO-N ha^{-1} h^{-1}. In the standard treatment, NO_x flux increased from 0.2 to 0.8, and



3 N Fertilizer Rates
Tomato
NOx
0 kg N
Standard
300 kg N /ha
g NOx-N ha-1 h-1
N2O
g N2O-N ha-1 h-1
Soil Temperature (1 cm)
Temperature (°C)
5/2/2011
5/21/2011
5/23/2011
6/2/2011
6/10/2011
6/17/2011
6/24/2011 06:30:00
6/24/2011 10:45:00
6/24/2011 16:10:00
7/14/2011
7/18/2011
7/21/2011
7/25/2011
8/9/2011
8/11/2011

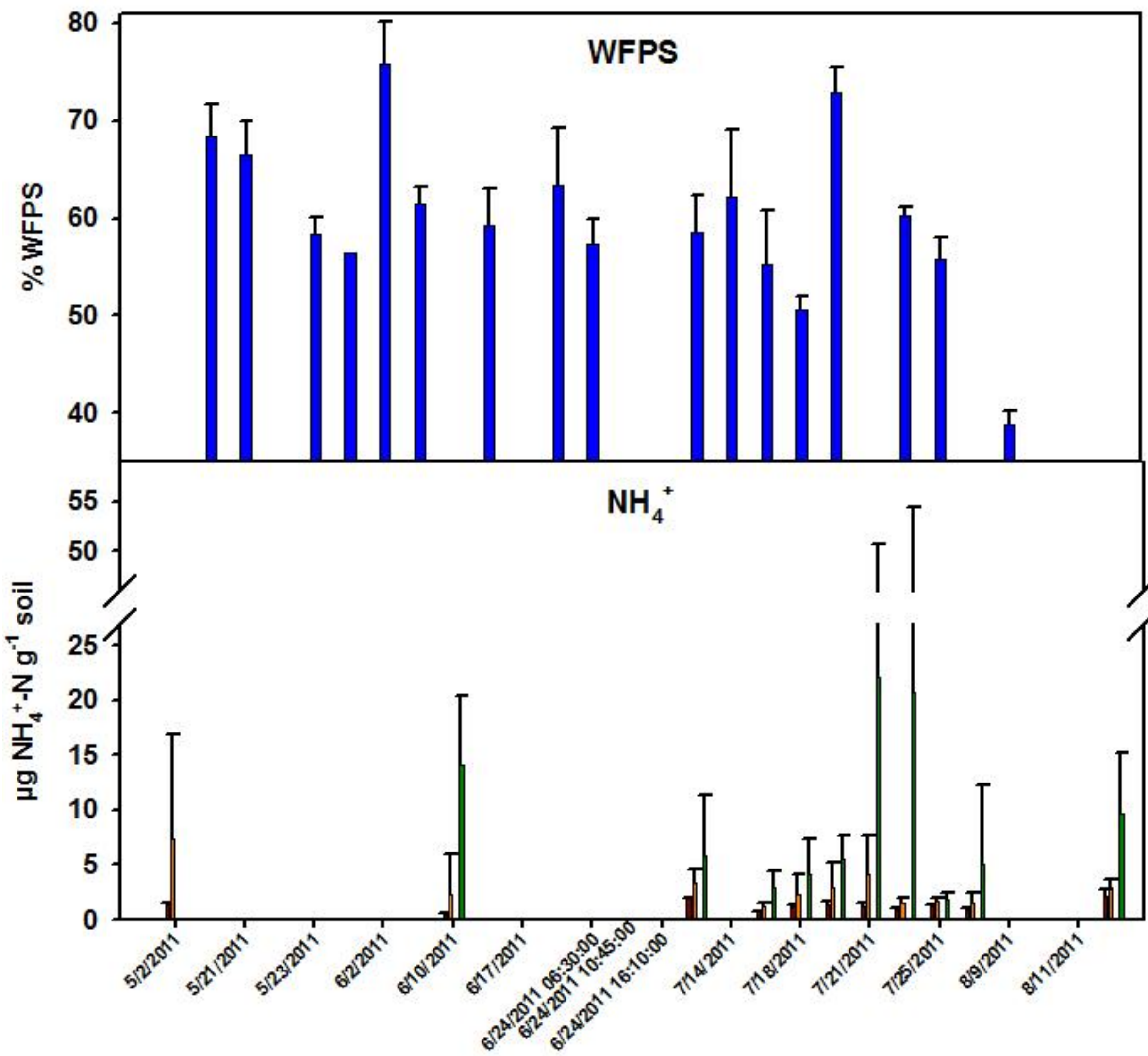
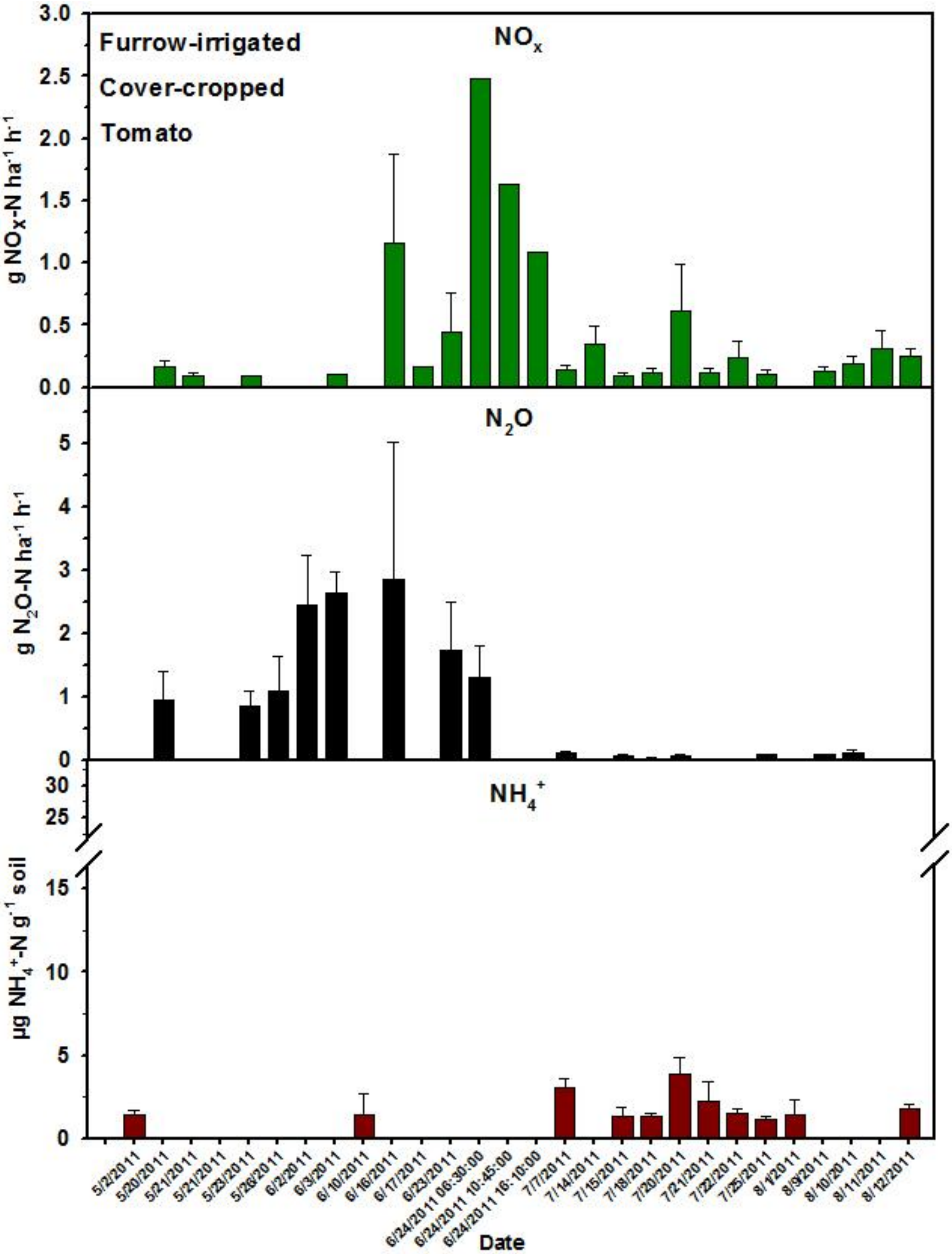


Figure 4. NO_x and nitrous oxide (N_2O) flux, soil temperature at 1 cm depth, water-filled pores space (WFPS), and soil ammonium (NH_4^+) concentrations in furrow-irrigated tomato fertilized at 300, 162 and 0 kg N ha^{-1}. Standard errors shown as line bars. n=3.

declined to 0.6 g NO-N ha^{-1} h^{-1} during that day. On the days both NO_x and N_2O flux were measured, the amount of N emitted as NO was on average about three times greater than the amount of N_2O-N in the high N treatment and about equal to that in the standard N treatment. The soil water content in the furrow-irrigated tomatoes was mostly between 55 and 70%. Soil NH_4^+ concentrations were 5-20 µg NH_4^+-N g^{-1} soil in the high N treatment, 1-3 µg NH_4^+-N g^{-1} soil in the standard N treatment, and <1.5 µg NH_4^+-N g^{-1} soil in the zero N treatment.

In the winter cover-cropped tomato system, the NO_x fluxes reached as much 2.5 g NO-N ha^{-1} h^{-1} on some days, but during the remaining period were mostly <0.5 g NO-N ha^{-1} (Figure 5.). The corresponding N_2O-N fluxes were similar in magnitude as the NO_x fluxes.



Furrow-irrigated
Cover-cropped
Tomato
NOx
g NOx-N ha-1 h-1
N2O
g N2O-N ha-1 h-1
NH4+
µg NH4+-N g-1 soil
Date
5/2/2011
5/20/2011
5/21/2011
5/21/2011
5/23/2011
5/26/2011
6/2/2011
6/3/2011
6/10/2011
6/16/2011
6/17/2011
6/23/2011
6/24/2011 06:30:00
6/24/2011 10:45:00
6/24/2011 16:10:00
7/7/2011
7/14/2011
7/15/2011
7/18/2011
7/20/2011
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8/10/2011
8/11/2011
8/12/2011

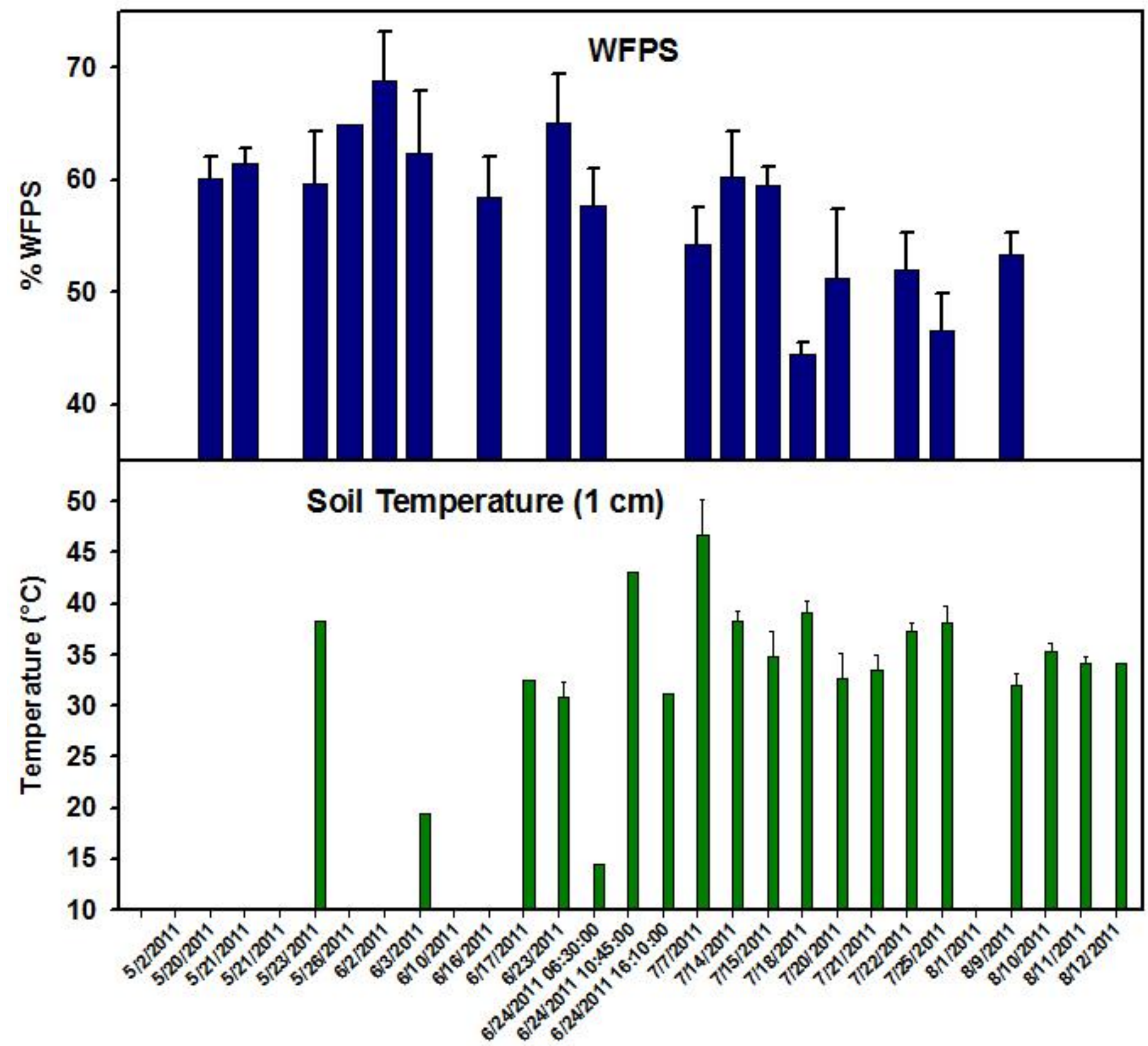
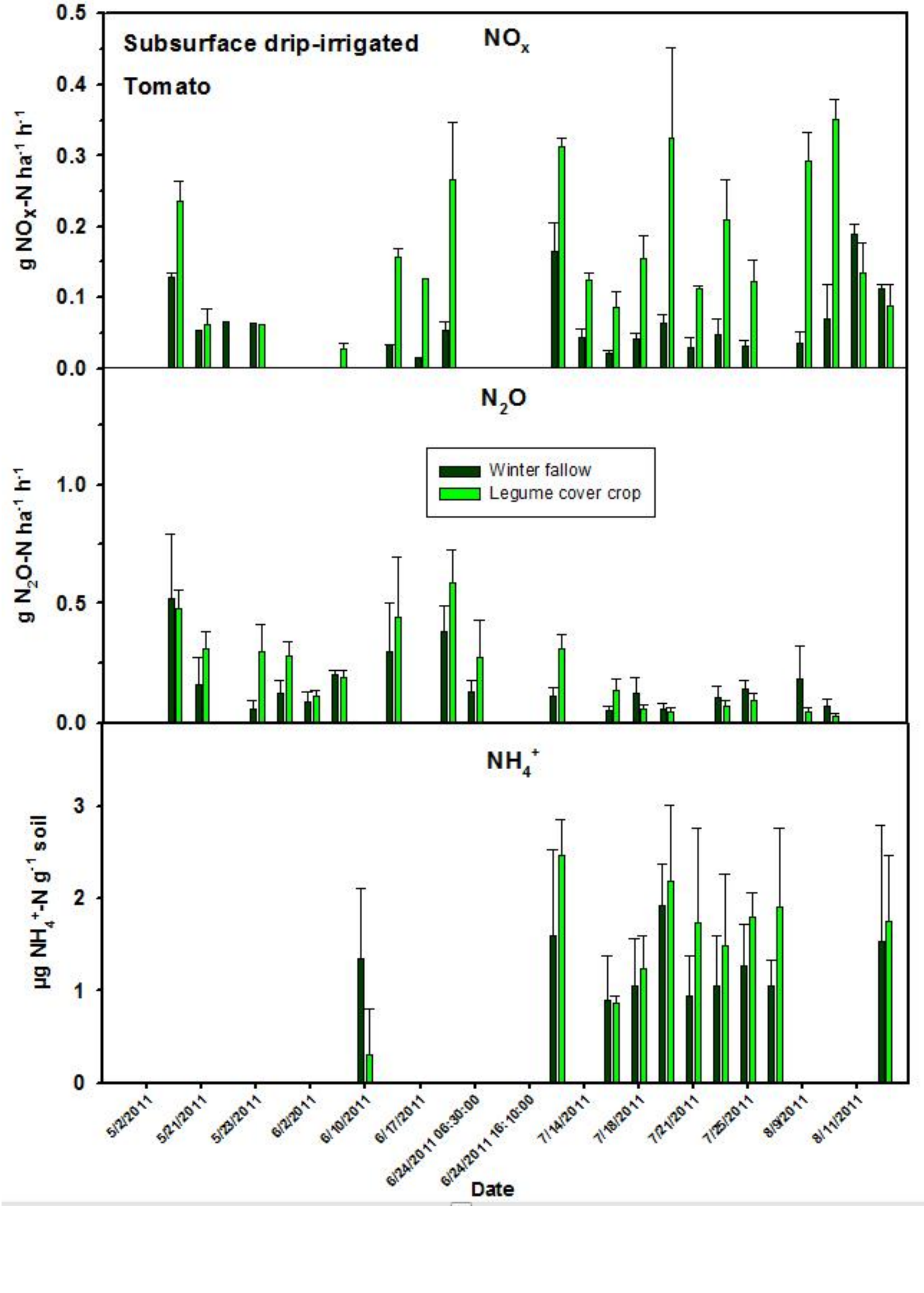


Figure 5. NO_x and nitrous oxide (N_2O) flux, soil ammonium (NH_4^+) concentrations, water-filled pores space (WFPS), and soil temperature in the furrow-irrigated, winter cover-cropped tomato system fertilized with 179 kg N ha^{-1} in cover cropped and winter-fallow tomato cropping systems. Standard errors shown as line bars. n=3.

Under SDI, the NO_x fluxes ranged from 0.01-0.3 g NO-N ha^{-1} h^{-1} (Figure 6). On most days the fluxes were measured the NO-N emissions were greater in the system a cover crop containing legumes had been grown the previous winter, whereas soil NH_4^+ concentrations were similar between the two SD-irrigated systems. The N_2O fluxes ranged from 0.05-0.5 g N_2O-N ha^{-1} h^{-1}. The WFPS ranged from about 35-50%.



Subsurface drip-irrigated
Tomato
NOx
g NOx-N ha-1 h-1
N2O
Winter fallow
Legume cover crop
g N2O-N ha-1 h-1
NH4+
µg NH4+-N g-1 soil
5/2/2011
5/21/2011
5/23/2011
6/2/2011
6/10/2011
6/17/2011
6/24/2011 06:30:00
6/24/2011 16:10:00
7/14/2011
7/18/2011
7/21/2011
7/25/2011
8/9/2011
8/11/2011
Date

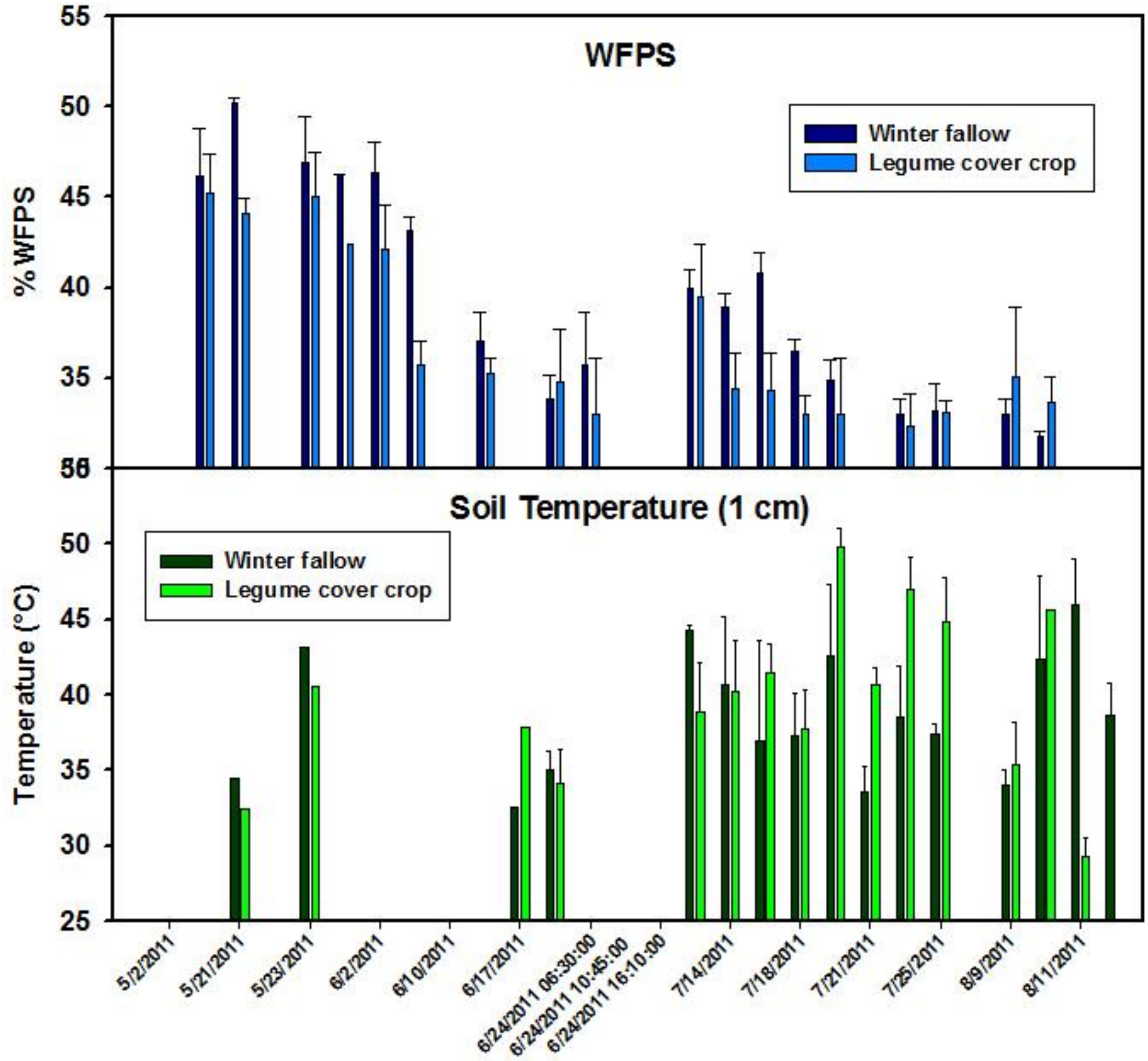


Figure 6. NO_x and nitrous oxide (N_2O) flux, soil ammonium (NH_4^+) concentrations, water-filled pores space (WFPS), and soil temperature in subsurface drip-irrigated tomato fertilized with 179 kg N ha^{-1} in cover cropped and winter-fallow tomato cropping systems. Standard errors shown as line bars. n=3.

3.4 *Wheat*

The NO_x fluxes measured in early summer in the wheat systems were between 9 and 70 mg NO-N ha^{-1} h^{-1} (Table 8). The N_2O-N fluxes in the N fertilized treatments were 10 to 40 times greater than the NO-N fluxes, and the NH_4^+ concentrations were between 1 and 2.5 μg NH_4^+-N g^{-1} soil.

Table 8. The NO_x and N_2O flux, soil ammonium concentrations, and water filled pore space in five wheat treatments at Dixon and Russell Ranch field sites.

Date	NOx (mg NO-N ha^{-1} h^{-1}	N_2O (mg N_2O-N ha^{-1} h^{-1})	NH_4^+ (μg NH_4^+-N g^{-1})	WFPS (%)
May 24, 2011				
Control	25.8 ± 7.7	10.0 ±3.5	1.6 ±1.2	46 ±4
AA & U	17.8 ±12.4	179.1 ±60.5	1.9 ±0.9	45 ±4
AS & U	9 ±10.9	108.5 ±60.7	0.9 ±0.2	46 ±4
May 30, 2012				
Wheat-T-fallow	69.5 ±22.7	1377 ±242	1.4 ±0.2	nd
Wheat-T-cc	55.4 ±4.8	2487 ±405	2.5 ±0.4	nd

Control = no N fertilizer applied; AA & U = 112 kg N ha^{-1} applied as anhydrous ammonia at planting and 98 kg N ha^{-1} applied as urea in February; AS & U = 168 kg N ha^{-1} applied as ammonium sulfate at planting and 98 kg N ha^{-1} applied in February; Wheat-T-fallow = wheat -tomato-fallow rotation; wheat-T-cc = wheat-tomato-cover crop rotation, wheat was fertilized with 112 kg N applied as urea at planting and 80 kg N ah-1 applied as foliar application in March.

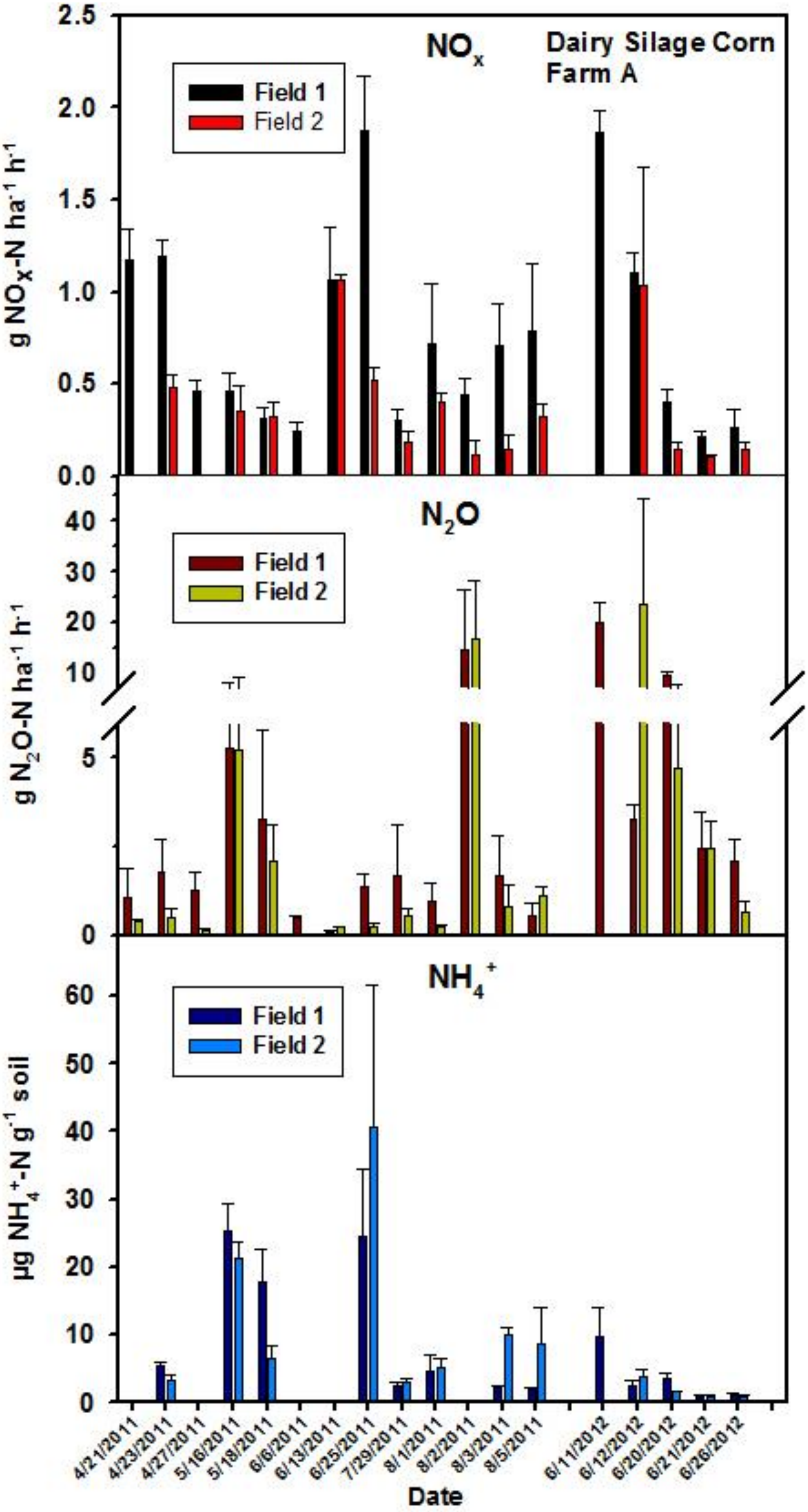
3.5 *Dairy silage corn*

The soil temperatures (1 cm depth) during measurements at all the sites were 25-40°C (Figures 7, 9, 10). The WFPS ranged from 50-80% at Farm A and from 40-80% at Farm B, but on Farm C, all WFPS measurements were >70% and sometimes reaching 100%.

In the fields of Farm A, the NO flux was mostly ≤1 g NO_x-N ha^{-1} h^{-1}, except for two days when NO_x flux reached about 2 g NO_x-N ha^{-1} h^{-1} (Figure 7). The soil NH_4^+ concentrations on one of those days was 25 μg NH_4^+-N g^{-1} (June 25, 2011), and 10 μg NH_4^+-N g^{-1} on the other (June 11, 2012). Soil NO_2^- concentrations were low on most days, and there was no correlation of NO_x flux with NO_2^- concentration in the soil. Nevertheless, the highest NOx flux occurred when NO_2^- was at the highest concentration (Figure 8). The N_2O fluxes were mostly <5 g N_2O-N ha^{-1} h^{-1}, reaching up to 20 g N_2O-N ha^{-1} h^{-1} on some days.

In two fields of Farm B, the NO_x fluxes were mostly <2 g NO-N ha^{-1} h^{-1}, but on two occasions (June 19, 2011 and June 15, 2012), NO_x fluxes reached >14 g NO_x-N ha^{-1} h^{-1} (Figure 8). On those two occasions the soil NH_4^+ concentrations were 140 and 50 μg NH_4^+-N g^{-1} soil.

At Farm C, the NO_x flux was mostly <1 g NO_x-N ha^{-1} h^{-1}, except between June 22 and 27, 2011, when NO_x fluxes reached up to 3.3 g NO_x-N ha^{-1} h^{-1} and between Sept 18 and 21, 2012, when NO_x fluxes up to 41 g NO-N ha^{-1} h^{-1} were recorded (Figure 10). At Farm C, NO_x fluxes in 2011 were mostly <0.5 g NO_x-N ha^{-1} h^{-1} except for three days (June 22 – June 27, 2011) when fluxes peaked at 3.3 g NO_x-N ha^{-1} h^{-1} (Figure 9). During that period, soil NH_4^+ concentrations were 7 μg NH_4^+-N g^{-1} and the WFPS was 96%. Soil NO_2^- concentrations during this period were about 4 μg NO_2^--N g^{-1} (Figure 11). In June 2012, the NO_x flux exceeded 1 g NO_x-N ha^{-1} h^{-1} on only one day (June 27) when soil NH_4^+ concentrations were 24 μg NH_4^+-N g^{-1} and the WFPS was 76%. In September 2012, the NO_x fluxes peaked at 42 g NO_x-N ha^{-1} d^{-1} (September 21) when soil NH_4^+ concentrations were 8 μg NH_4^+-N g^{-1} and the WFPS was 88%. The N_2O flux at Farm C in both years was elevated in June, with fluxes up to 30-40 g N_2O-N ha^{-1} h^{-1}, but in September 2012, peak N_2O fluxes were lower than the NO_x fluxes.


NOx
Dairy Silage Corn
Farm A
Field 1
Field 2
g NOx-N ha-1 h-1
N2O
Field 1
Field 2
g N2O-N ha-1 h-1
NH4+
Field 1
Field 2
µg NH4+-N g-1 soil
4/21/2011
4/23/2011
4/27/2011
5/16/2011
5/18/2011
6/6/2011
6/13/2011
6/25/2011
7/29/2011
8/1/2011
8/2/2011
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8/5/2011
6/11/2012
6/12/2012
6/20/2012
6/21/2012
6/26/2012
Date

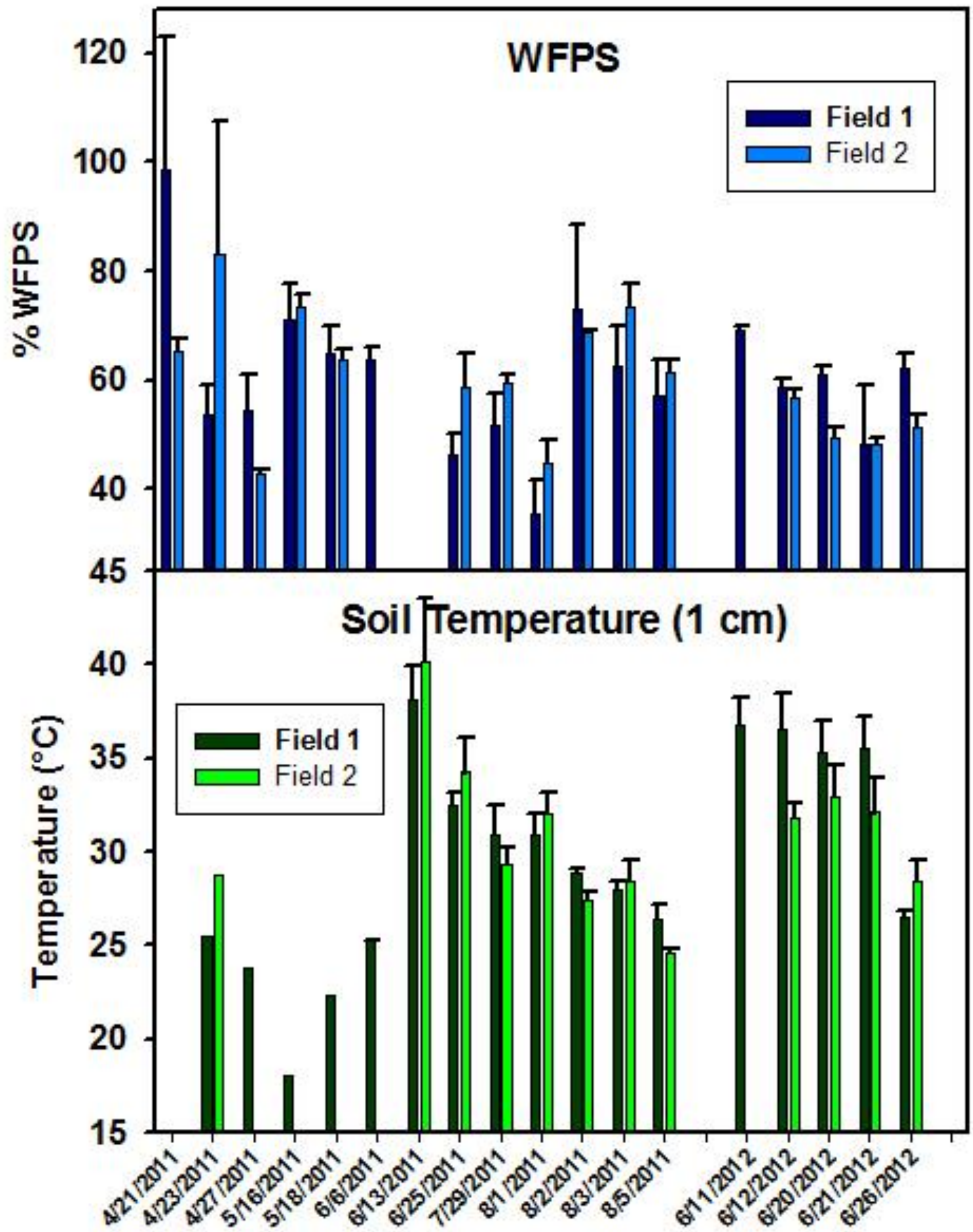


Figure 7. NO_x and nitrous oxide (N_2O) flux, soil ammonium (NH_4^+) concentrations, water-filled pores space (WFPS), and soil temperature in the dairy silage corn systems of Farm A. Standard errors shown as line bars. n=4.

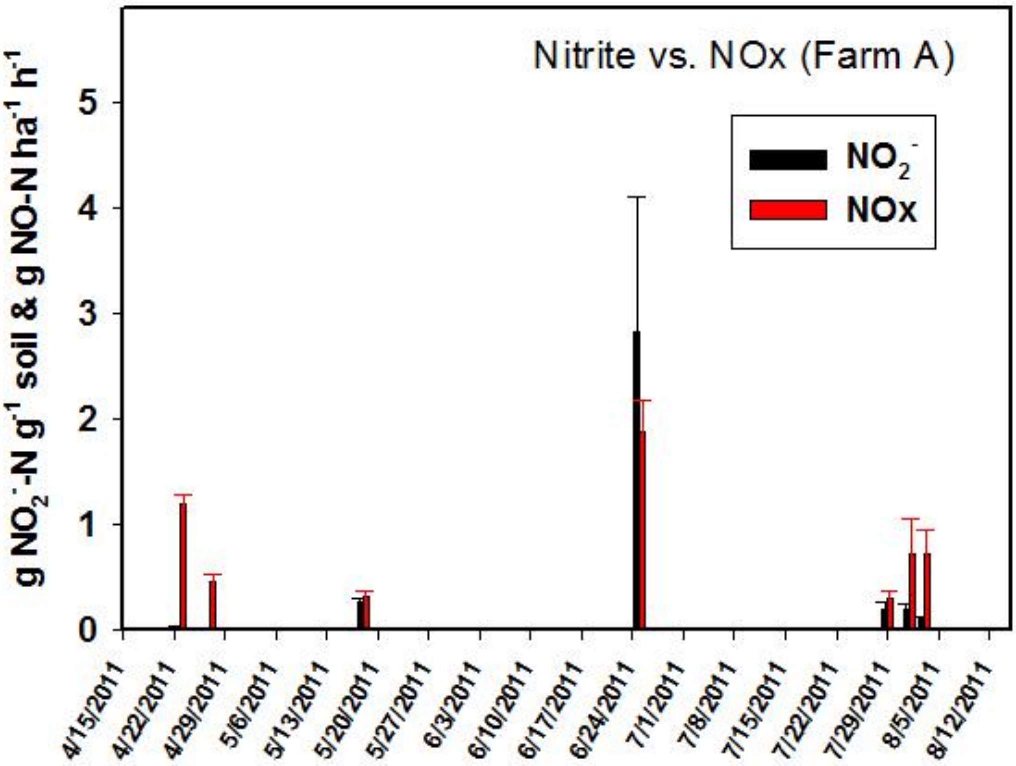
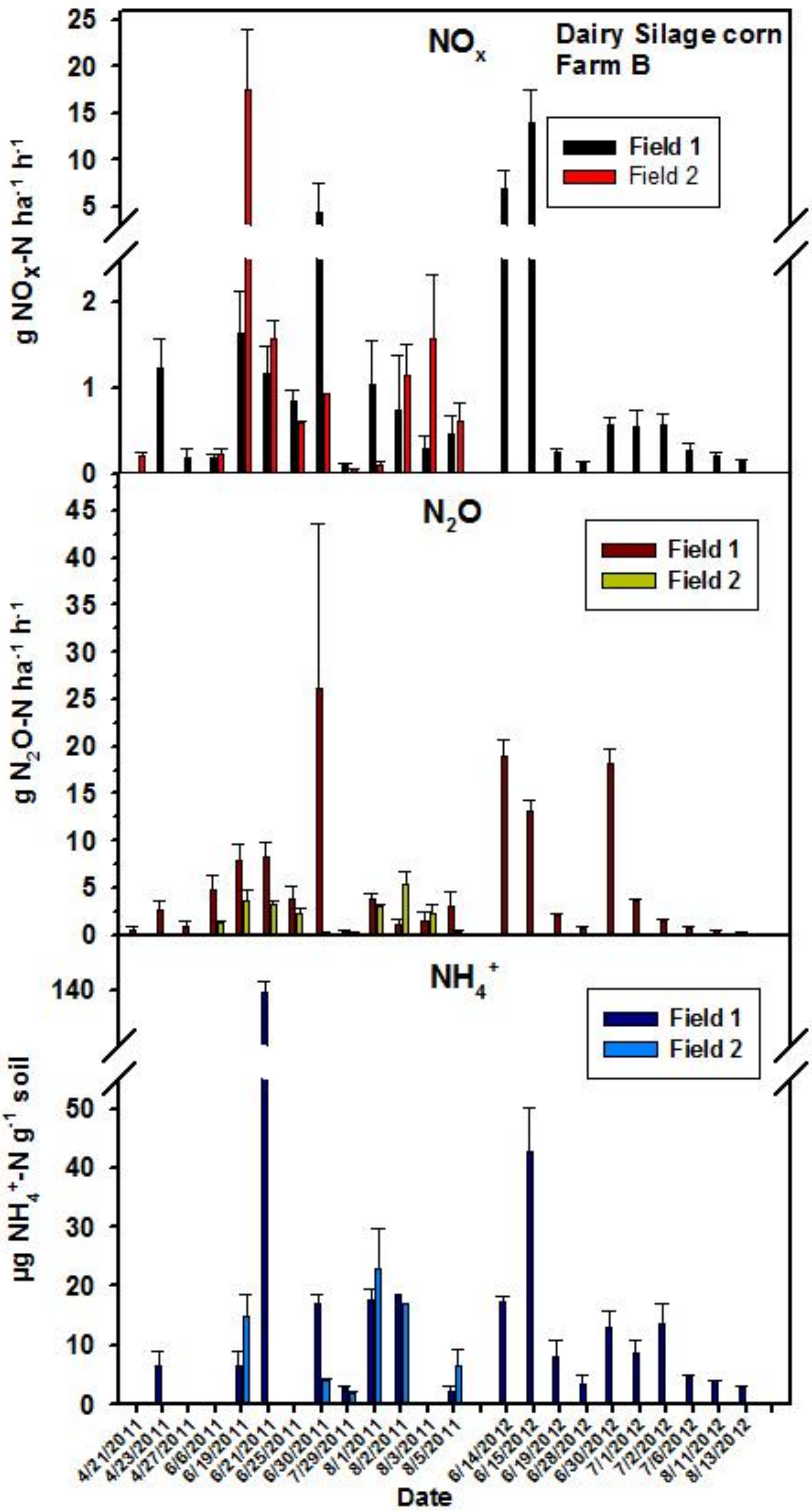


Figure 8. Soil nitrite concentrations vs. NO_x flux at Farm A. Standard errors shown as line bars. n=4.



NO$_x$
Dairy Silage corn
Farm B
Field 1
Field 2
g NO$_x$-N ha^{-1} h^{-1}
N$_2$O
Field 1
Field 2
g N$_2$O-N ha^{-1} h^{-1}
NH$_4^+$
Field 1
Field 2
µg NH$_4^+$-N g^{-1} soil
4/21/2011
4/23/2011
4/27/2011
6/6/2011
6/19/2011
6/21/2011
6/25/2011
6/30/2011
7/29/2011
8/1/2011
8/2/2011
8/3/2011
8/5/2011
6/14/2012
6/15/2012
6/19/2012
6/28/2012
6/30/2012
7/1/2012
7/2/2012
7/6/2012
8/11/2012
8/13/2012
Date

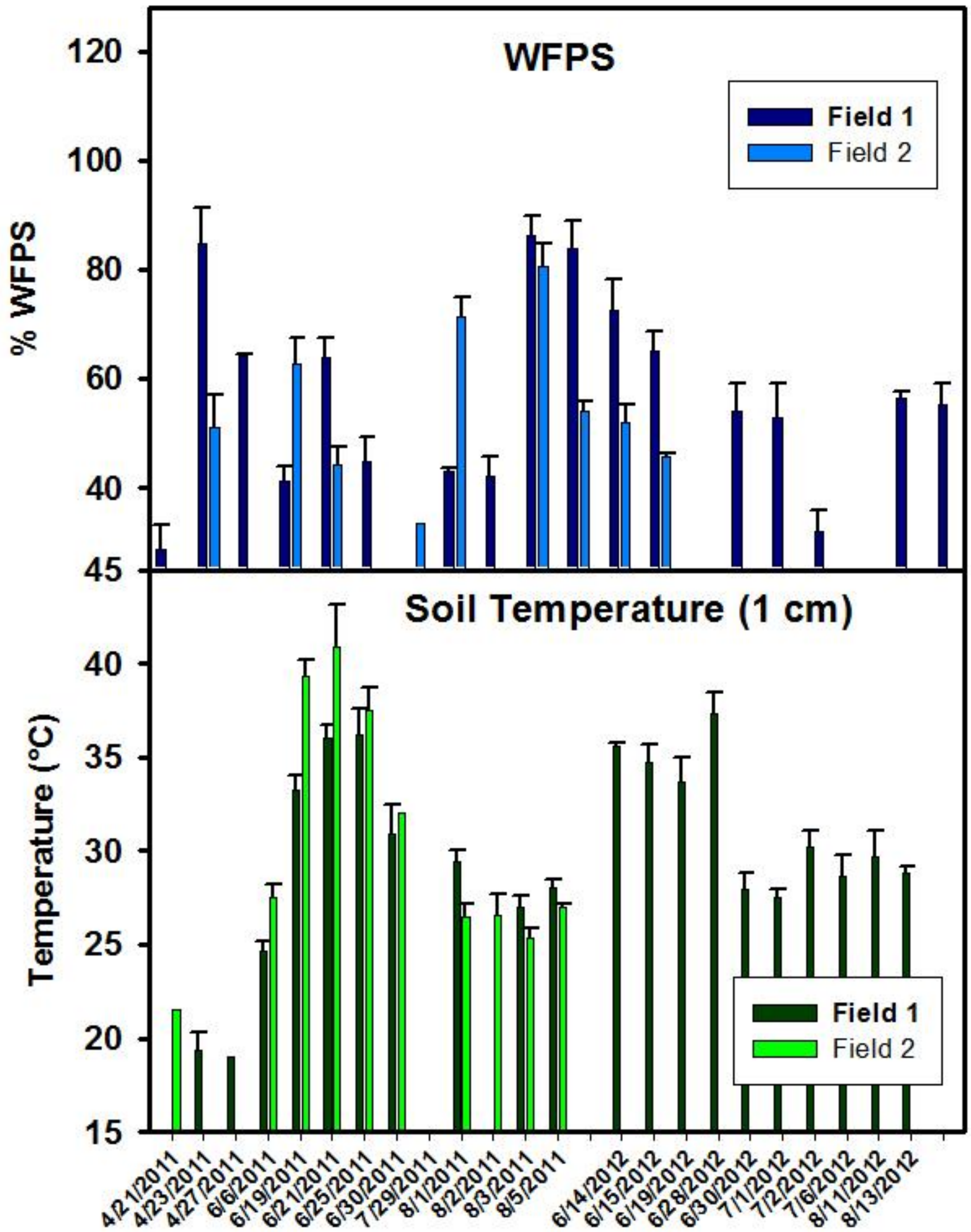
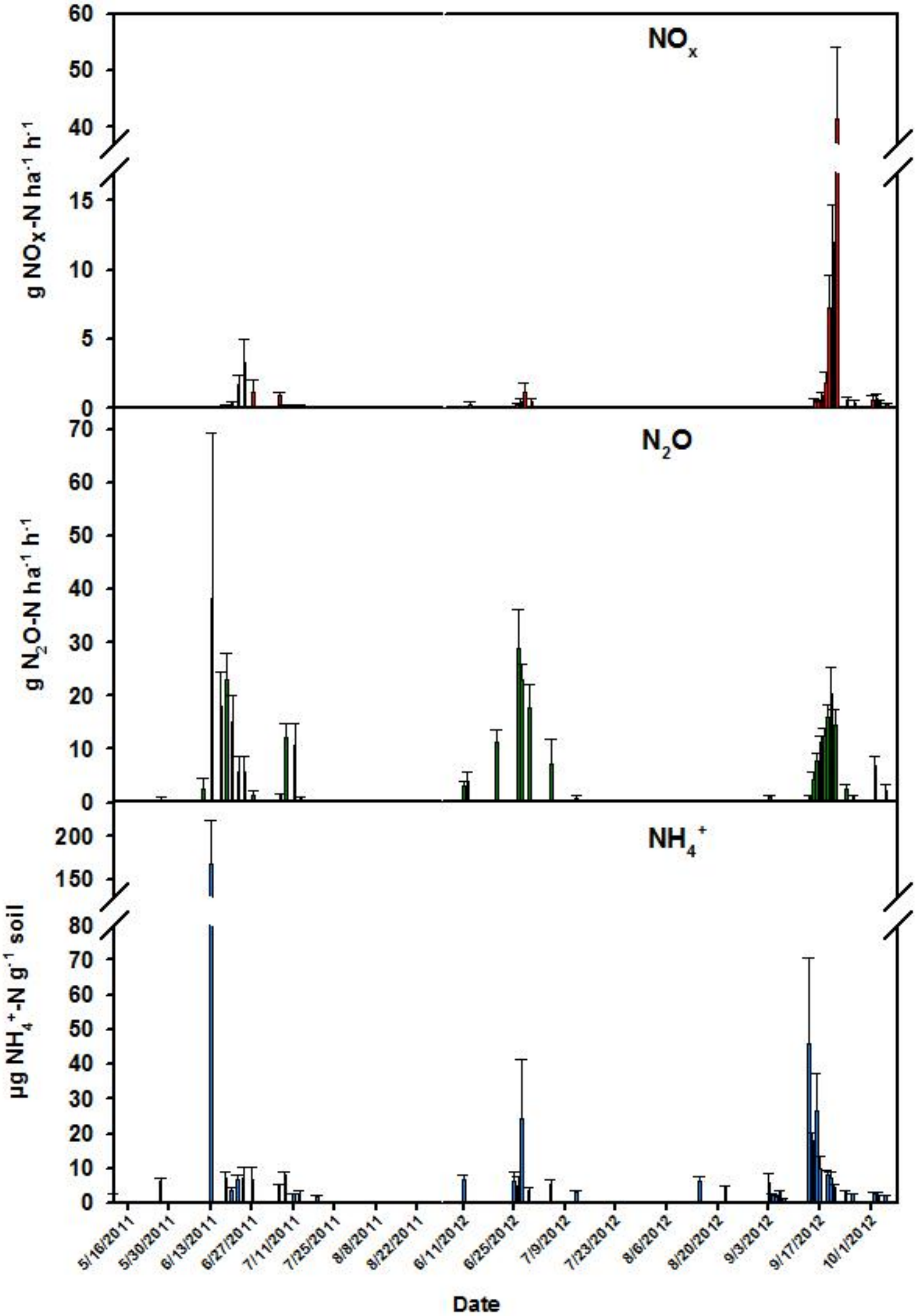


Figure 9. NO_x and nitrous oxide (N_2O) flux, soil ammonium (NH_4^+) concentrations, water-filled pore space (WFPS), and soil temperature in the dairy silage corn systems of Farm B. Standard errors shown as line bars. n=4.



NOx
g NOx-N ha-1 h-1
N2O
g N2O-N ha-1 h-1
NH4+
µg NH4+-N g-1 soil
5/16/2011
5/30/2011
6/13/2011
6/27/2011
7/11/2011
7/25/2011
8/8/2011
8/22/2011
6/11/2012
6/25/2012
7/9/2012
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8/6/2012
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9/3/2012
9/17/2012
10/1/2012
Date

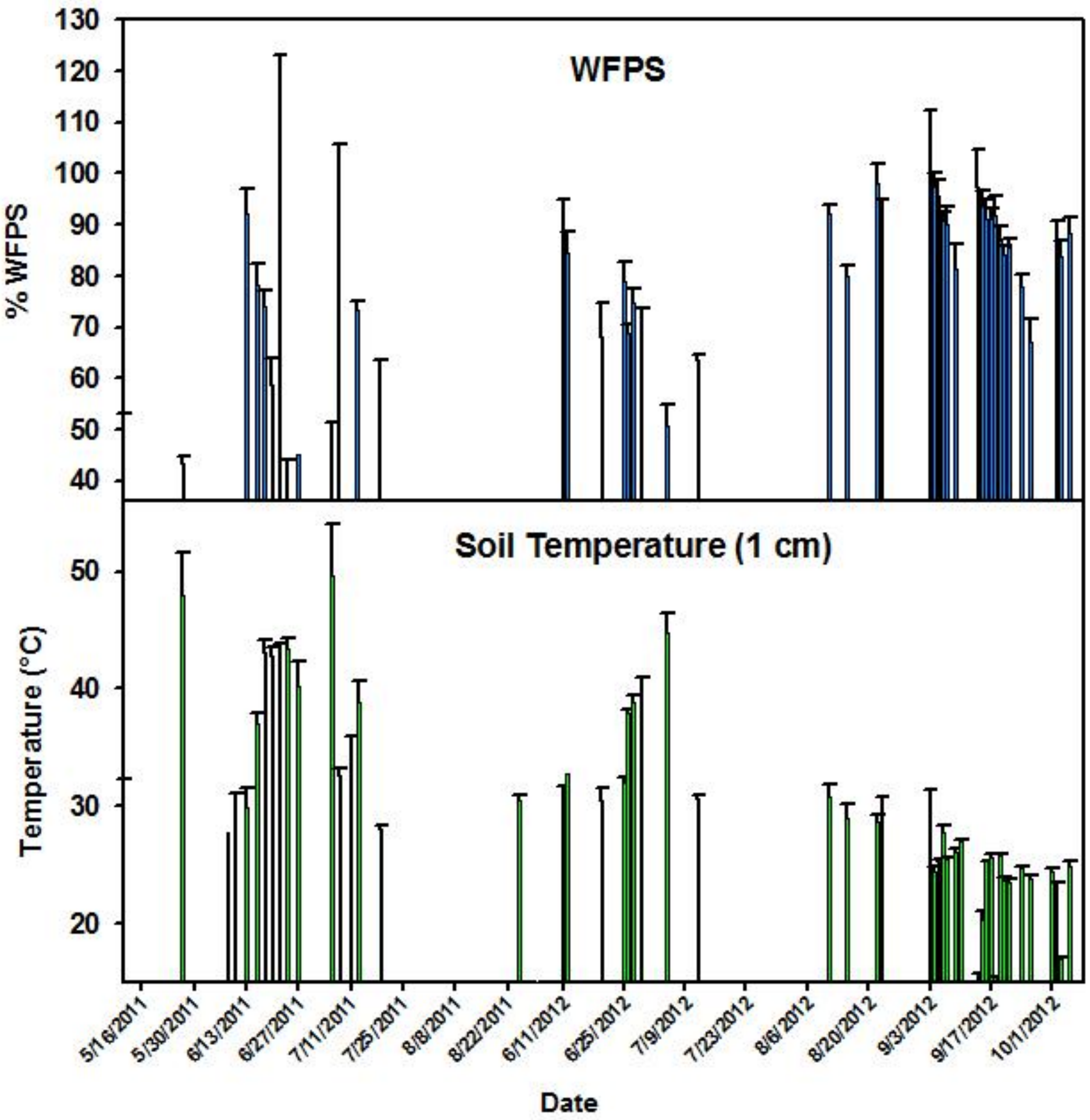

Figure 10. NO_x and nitrous oxide (N_2O) flux, soil ammonium (NH_4^+) concentrations, water-filled pore space (WFPS), and soil temperature in the dairy silage corn systems of Farm C. Standard errors shown as line bars. n=4.

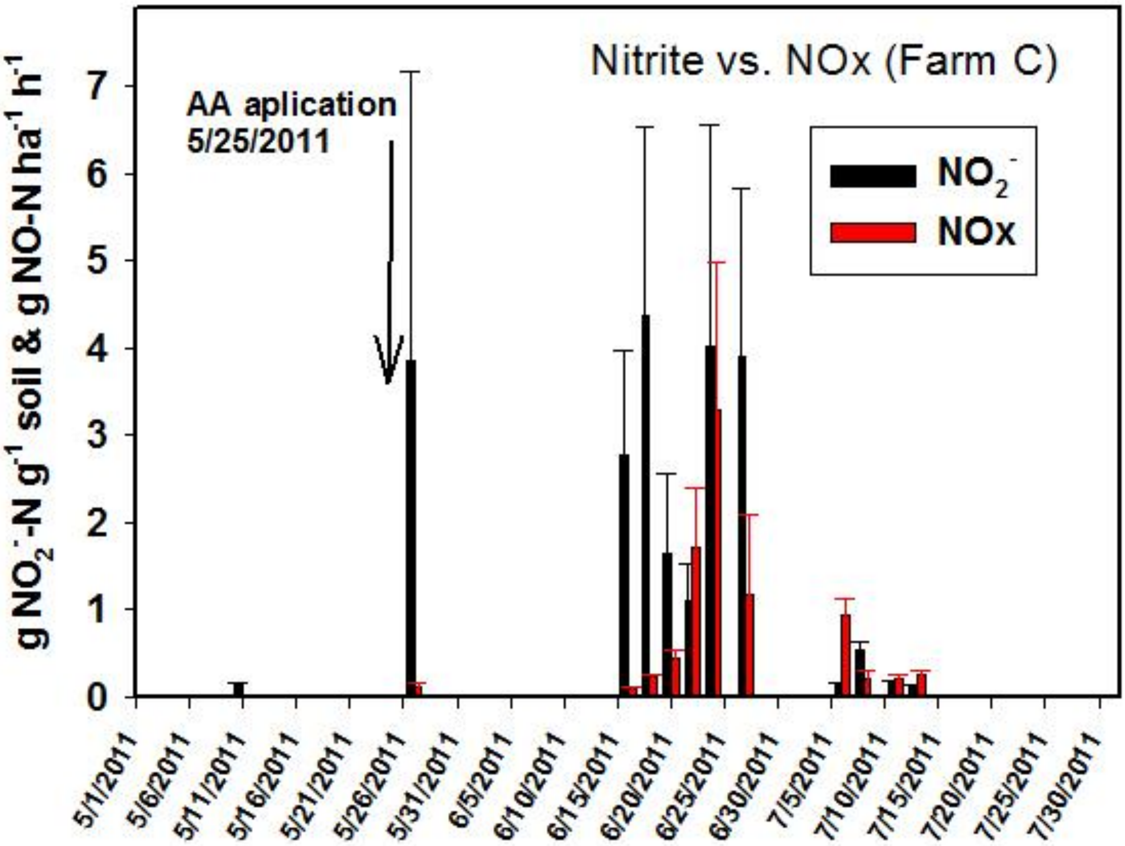

Figure 11. Soil nitrite concentrations vs. NO_x flux at Farm C. The date of the anhydrous ammonia (AA) application is also shown. Standard errors shown as line bars. n=4.

3.6 *Relationship between NOx flux and soil temperature*

The NO_x-flux in response to temperature change, expressed as the change in rate per 10°C change in soil temperature (Q_{10}) at 1 and 5 cm depth, was determined at 8 experiments at some of the field sites. The Q_{10} ranged from 1.2-3.8 with a mean of 2.5 based on soil temperature changes at 1 cm depth, and from 1.3-5.2 with a mean of 3.4 based on soil temperature changes at 5 cm depth (Table 9). Figure 11 shows data from three sites adjacent to and inside a corn field. Each data point shown represents an individual measurement.

Table 9. Q_{10} of NO_x-flux based on the change in soil temperature at 1 and 5 cm depth

Location Date		Min. T. 1 cm (°C)	Max. T. 1 cm (°C)	Min. T. 5 cm (°C)	Max. T. 5 cm (°C)	Q_{10} 1 cm	Q_{10} 5 cm
C1	7/21/12	18.8	45.8	21.2	42.2	1.8	2.0
C2	7/21/12	18.2	49.9	21.7	46.8	2.4	3.0
C3	7/21/12	17.1	32.5	18.2	32.5	3.8	4.4
FB	8/10/12	19.8	29.2	20.4	27.6	1.6	2.1
FC	9/15/12	15.6	25.3	17.5	23.5	3.0	4.2
FC	9/16/12	15.3	25.0	16.0	23.2	1.9	2.5
FC	9/26/12	16.8	24.9	16.9	23.0	1.2	1.3
FC	10/3/12	15.9	25.2	17.2	23.6	3.0	5.2
Mean						2.5	3.4

C1-C3 = Campbell Tract, UC Davis; FB = Farm B; FC = Farm C

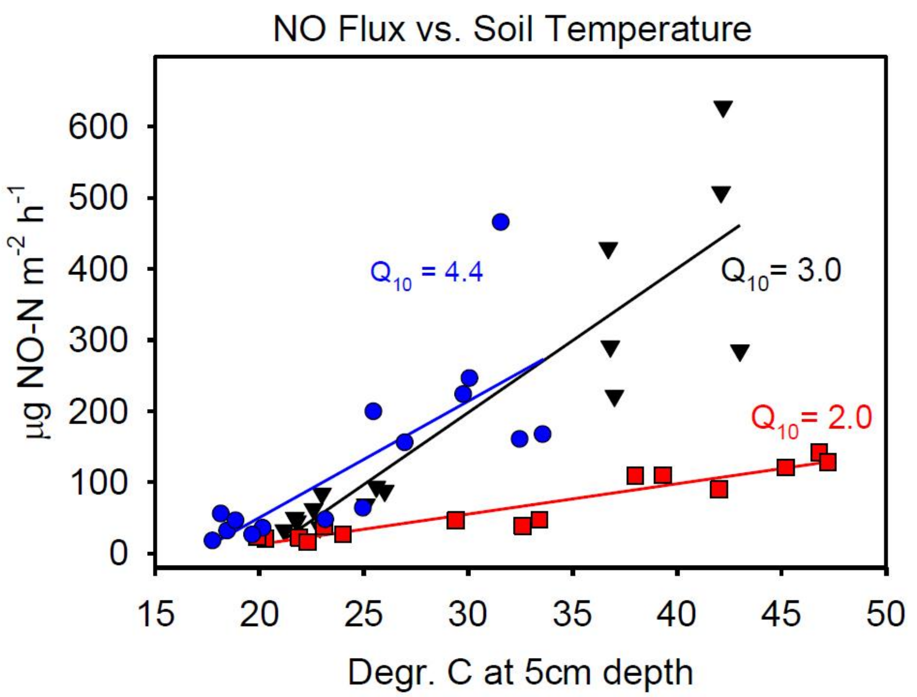

Figure 11. NO_x-flux in relation to soil temperature at 5 cm during the course of one day at three locations of a corn field.

4. Discussion

We measured NO_x fluxes under varied soil moisture conditions in five different cropping systems receiving N inputs at different rates and in varied forms, and we calculated average hourly fluxes for each treatment and system. The average hourly fluxes provide information on the general trends in emissions among the different systems studied (Table 7). The lowest fluxes were observed in the wheat systems, the tractor rows of the almond orchard, the furrow-irrigated tomato control treatment (no N fertilizer applied this season) and the two SDI treatments of the tomato systems (Table 7). Somewhat greater average hourly NO_x fluxes were measured in alfalfa, the tree rows of the almond orchard, and the FI treatments of the tomato systems fertilized at recommended N rates. Our results are in agreement with those of earlier studies in California cropping systems. For alfalfa, except for one day, the measured fluxes in this study ranged from 0.07-0.6 g NO-N ha^{-1} h^{-1}, which is very similar to earlier reported ranges of 0.1-0.6 (Matson and Firestone, 1995). Likewise, the range of emissions in the sprinkler irrigated almond orchard in our study was 0.02-1.09 vs. 0.1-0.9 g ha^{-1} h^{-1} in the previous study, and for FI tomatoes the corresponding ranges are 0.04-1.2 vs. 0.1-1.2 g NO-N ha^{-1} h^{-1} (Matson and Firestone, 1995). In the systems receiving high N inputs, such as FI tomatoes fertilized with 300 kg N ha^{-1} and the dairy silage corn systems, the average NO_x fluxes were between 0.4 and 2.8 g NO_x-N ha^{-1} h^{-1} and higher than in the other systems studied here. There are not many field data of NO_x emissions resulting from liquid manure applications in the literature. Although on most days the range of fluxes measured by us in corn systems was similar as in a previous study (0.01-5.2 g NO_x-N ha^{-1} h^{-1}) (Matson and Firestone, 1995), we also recorded some fluxes that exceeded those values by a wide margin and were comparable to those reported for fertilized (184 kg N as urea and 63 kg N as anhydrous ammonia) irrigated wheat systems in Sonora, Mexico (peak fluxes of 20-55 g NOx-N ha^{-1} h^{-1})(Matson *et al.*, 1998), and with the fluxes measured above an injection band of anhydrous ammonia (120 kg N ha^{-1}) in a California tomato system (5-10 g NO_x-N ha^{-1} h^{-1}, with peak values of up to 100 g NO_x-N ha^{-1} h^{-1})(Venterea and Rolston, 2000b).

Nitric oxide flux is highly dependent on temperature, with a predicted doubling of NO production for each 10°C increase in temperature between 15° and 35°C (Williams *et al.*, 1995). Most of our NO_x flux measurements were made in the afternoons. The recorded fluxes therefore represent values close to the maximum of those days. If the reported NO_x emission values will be used as modeling inputs, the fluxes need to be adjusted for diel fluctuations in temperature. We derived Q_{10} factors under field conditions in three different corn cropping systems. The lowest NO_x flux of the day was always measured early in the morning when soil temperatures typically are at their daily minimum. The ranges of Q_{10} varied from 1.2 to 3.8 with a mean of 2.5 based on soil temperature dynamics at a depth of 1 cm. Based on soil temperature at 5 cm, the range was 1.3-5.2 with a mean of 3.5 (Table 9). The Q_{10} obtained based on soil temperature at 1 cm may have been lower because nitrifying bacteria have been reported to stop growing >40°C (Focht and Verstraete, 1977). Temperatures at 1 cm depth were approaching or exceeding this temperature on some of the days and were higher than at 5 cm depth.

Besides temperature, availability of the substrate NH_4^+ and NO_2^-, as influenced by the amount, form, and placement of N inputs, controls NO_x flux. For example, on Farm B, NO_x-fluxes of 10-15 g NO-N ha^{-1} h^{-1} were measured shortly after UAN32 fertilizer applications on June 15, 2011 and June 7, 2012, and an irrigation with lagoon water. The high NO_x emissions also coincided with NH_4^+ concentrations >100 μg NH_4^+-N g^{-1}. In the tomato system, the application of 300 kg N ha^{-1} as UAN32 - almost twice the recommended N rate for furrow-irrigated tomato crops - lead to sustained high NO_x emissions lasting about 6 weeks. It is possible that in the dairy silage corn systems the liquid manure enhanced NO_x emissions due to the availability of carbon which stimulates O_2 consumption in the soil. Nitric oxide and N_2O production increase with decreasing O_2 levels in the soil (Zhu *et al.*, 2013). Nitrite, the intermediate during ammonia oxidation to NO_3^- is a precursor of NO and N_2O in the soil (VanCleemput and Samater, 1996; Venterea and Rolston, 2000a, b; Zhu *et al.*, 2013). We detected NO_2^- after application of anhydrous ammonia (Farm C) and after application of liquid manure and UAN in the irrigation water at Farm A, and in both cases enhanced NO_x emissions coincided with high NO_2^- levels in the soil (Figures 8 and 11). There was also a weak correlation of NO_x flux with NO_2^- levels in the almond orchard (Figure 2).

Since most NO produced in soil is consumed to produce N_2O (Venterea and Rolston, 2000b; Venterea *et al.*, 2004), the placement of the substrate can be expected to affect the magnitude NO_x emissions. Diffusion of gases at high WFPS is low, and consumptive processes of NO are likely favored over the release of this reactive gas to the atmosphere. In general, during the periods when high NO_x emissions occurred, the WFPS was ≤60%, but there were some noteworthy exceptions. For example, in September 2012, NO_x fluxes on the order of 7-42 g NO-N ha^{-1} h^{-1} occurred at Farm C while WFPS was >90%. The high NO_x emissions took place in spite of high WFPS most likely because the liquid manure, which was applied via flood irrigation, provided the substrate (NH_4^+) for nitrification and NO_x production near the soil surface. It is interesting that in June, 2011, substantial NO_x flux following the anhydrous ammonia application at Farm C did not occur until WFPS declined to <50% (Figure 10) even though NO_2^- concentrations were elevated as soon as the anhydrous ammonia was applied (Figure 11).

The NO_x emissions were related to N inputs and NH_4^+ availability, and most NO_x emitted was likely due to nitrification. Once most of the applied NH_4^+ was converted to NO_3^- or taken up by the crops, the NO_x fluxes subsided. This was particularly evident at Farm C, where lower NH_4^+ concentrations in the soil coincided with tapering off of NO_x flux. Similarly, as soil NH_4^+ concentrations decreased from >100 μg NH_4^+-N g^{-1} on Farm B, the NO flux subsided to more moderate levels. In the almond orchard, following four fertigation events, there were four distinct peaks of NO_x emissions, which declined over the course of 10 days probably because the NH_4^+ was taken up by the trees or nitrified although the decrease in NH_4^+ concentrations was not clearly shown. It appears, therefore, that in general NO_x fluxes decrease with time since N fertilization, which has been observed earlier (Williams *et al.*, 1992; Matson and Firestone, 1995).

The relationship between N_2O-N and NO_x-N fluxes varied, depending on the system. For alfalfa, the N_2O fluxes on the days of the measurements were greater by an order of magnitude. This was also the case in one of the dairy silage corn systems (Farm A) in June (2011, 2012). On the other hand, in the high N treatment of the furrow-irrigated tomato systems, the flux of NO_x-N was mostly greater than N_2O-N. This observation may be explained by soil water content. While N_2O production can be expected to be related to NO_x production, the opportunity for the consumption of NO_x is likely greater at high water content. Therefore, at high WFPS, N_2O tend to be greater than NO_x emissions.

Summary and Conclusions

Emissions of NO_x were measured in almond, alfalfa, tomato, wheat, and silage corn cropping systems during summer months (June-September) in the California Central Valley. The study was undertaken to estimate the contribution of NO_x from agricultural soil in order to improve the predictive power of ozone (O_3) models for the San Joaquin Valley since NO_x availability under certain circumstances (e.g. when the availability of volatile organic compounds is high) controls O_3 formation. The NO_x fluxes were measured with a portable NO_x analyzer in 17 different fields or treatments representing varied soil moisture conditions, nitrogen availability, and management practices, such as irrigation and nitrogen inputs.

The average NO_x fluxes were lowest in wheat, the non-irrigated sections of an almond orchard and in subsurface drip-irrigated tomato, and intermediate in alfalfa, the irrigated sector of an almond orchard, and furrow-irrigated tomato N fertilized at recommended rates. The highest NO_x emissions were measured in furrow-irrigated tomato fertilized at an excessive N rate and in silage corn systems receiving high N inputs in the form of synthetic N fertilizers and manure from dairy farms. The emissions at each location varied over time, depending on soil moisture, temperature and time since N fertilization. Field experiments showed that NO_x emissions increase on average 2.5- and 3.5-fold with each increase of 10°C in soil temperature at 1 and 5 cm depth, respectively. The ranges of emissions near their daily maximum were comparable to those measured in earlier studies in the different systems, but following high N inputs, the emissions were higher (by an order of magnitude) for short periods (days) and matched those of the highest peak NO_x fluxes ever measured from soil sources. Enhanced NO_x fluxes occurred under intermediate soil water contents (water-filled pore space 30-60%), whereas in relatively dry soils or at high water content, NO_x-fluxes were low. The results suggest that NO_x emissions are related to ammonium availability and nitrification rates.

Recommendations

Based on this relatively limited data set given the great variety of cropping systems in the San Joaquin Valley, it appears that N fertilization at recommended N rates does lead to fairly predictable NO_x emissions. However, the magnitude and duration of enhanced NO_x emissions (increased by an order of magnitude or more), are not necessarily predictable because they are event-based (e.g. date of N fertilization) and depend on complex interactions among NO production, gas transport and NO consumption in the soil, as well as other variables such as soil temperature at different depths.

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Glossary of Terms, Abbreviations and Symbols

AB32	Assembly Bill 32
CARB	California Air Resources Board
C	Carbon
°C	Degree(s) Celsius
cc	Cover crop
CrO_3	Chromium trioxide
FI	Furrow irrigation
h	Hour(s)
ha	Hectare
H_2O	Water
N	Nitrogen
NH_4^+	Ammonium
NO	Nitric oxide
NO_2^-	Nitrite
NO_3^-	Nitrate
NO_x	Nitric oxide and nitrogen dioxide
N_2O	Nitrous oxide
O_2	Oxygen
O_3	Ozone
PTFE	Teflon
PVC	Poly-vinyl chloride
SDI	Subsurface drip irrigation
UAN32	Urea ammonium-nitrate
UC	University of California
VOC	Volatile organic compounds
WFPS	Water-filled pore space
yr	Year