Carbon Sequestration Opportunities and Greenhouse Gas Production in Almond Orchards

Project No.: **08-AIR2-Smart**

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Objectives:

1) Constrain annual and event related N_2O, CO_2 and CH_4 emissions from orchards using two different forms of nitrogen fertilizer (Urea Ammonium Nitrate, UAN32 and Calcium Ammonium Nitrate, CAN17).
2) Evaluate spatial (and temporal) heterogeneity of N_2O (and CH_4) fluxes (Obj 1) with respect to environmental factors (soil N and fertilizer N, temperature, moisture, texture etc.) spatial structure of orchards (drip or microspray fertigation versus non-fertigated inter-row spaces).
3) Assess total below ground carbon allocation of almond orchards in order to acquire more comprehensive information on potential carbon sequestration.

Interpretive Summary:

The specific long-term goals are to identify and fill knowledge gaps on greenhouse gas (GHG) emissions/sequestration in almond orchards, and identify practices that can further diminish GHG emissions. In order to do this, we need comprehensive information on how management practices contribute to the overall net production and consumption of the three primary greenhouse gases produced by agricultural practices, which are carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4).

Global climate change is associated with increases in atmospheric concentrations of greenhouse gases (GHGs) such as CO_2, N_2O and CH_4. The global increase in temperature, for example, has been indisputably linked to the increase of GHGs in the atmosphere (IPCC, 2007), and is projected to seriously impact upon the natural resources, environment and agricultural economy of the state of California (Hayhoe *et al.,* 2004). California is the 12th major global emitter of GHG's, emitting approximately 500 million metric tons of carbon equivalents[ǂ] per annum. Of the total GHG emissions released by all sectors in the United States, approximately 84% of these emissions are from CO_2, with 7% and 6% from N_2O and CH_4 respectively, and similar estimates apply to California, where approximately 12% of the total emissions are derived from agricultural activities (Carlisle et al. 2009).

The GHG carbon dioxide is largely generated via fossil fuel combustion by tractors and other energy consuming operations in agriculture, but also from the oxidation of organic substances in soils (decomposition). It includes biological respiration of roots and trees which cannot be easily separated from CO_2 produced by decomposition in soils, and biomass burning (IPCC, 2007). In addition to CO_2, the other two major GHG's emitted as a direct consequence of agricultural practices are N_2O and CH_4 (De Vries *et al.,* 2005). Small amounts of N_2O are also produced by fossil fuel combustion in the industrial and transportation sectors, (Kebreab *et al.,* 2006) but net increases in N_2O in the atmosphere are primarily due to agricultural practices, which are thought to contribute to more than 70% of N_2O emissions. The primary practice implicated in N_2O production concerns nitrogen fertilizer applications, which results in acceleration of microbial transformations of nitrogen by nitrification and denitrification that directly and indirectly produce N_2O. The largest biogenic sources of CH_4 are from enteric fermentation by animals, rice production, organic fertilizer storage, biomass burning and via the anaerobic production of CH_4 in aquatic systems and soils from the microbial process of methanogenesis. Nonetheless, soils can consume CH_4 and developing a total GHG budget for almond, or, for example, providing third party verification for entering into carbon markets generally requires documentation of the production and consumption of all three gases.

Of concern to the California perennial crops industry is not just that predicted increases of these GHG's in the atmosphere, and resultant changes in regional temperature and seasonal precipitation are expected to adversely affect and production of California's specialty crops through diminished yields, diminished quality and shifts in suitable growing regions (Gentile et al. 2006). Mounting concern regarding increases in GHG's has resulted in the State legislature adopting the California Global Warming Solutions Act of 2006 (AB 32) in June of 2006. This initiative enables the State to begin imposing GHG emissions caps on sectors such as electricity and transportation. In light of this piece of legislation, and the potential for a carbon credit system, our research is accounting for carbon stocks and GHG emissions both produced and consumed (e.g. carbon sequestration) within an almond orchard. This has enabled us to prepare annual GHG budgets under “normal” management practices and to identify the major knowledge gaps for such an assessment. This budget may be utilized to investigate the ways in which almond orchards are already contributing to GHG mitigation (net emissions reductions through soil and aboveground carbon sequestration).

To date, our findings suggest that N2O emissions are strongly spatially constrained to irrigation and fertilization events. By using modeling exercises and empirical data gathered through this project we are beginning to better estimate emissions in a way that is more indicative of GHG emissions scenarios for Mediterranean irrigated agriculture. Our results also indicate not only those large inter-row areas in almond orchards have greatly diminished emissions, but also that irrigation management plays a definitive role. Microjet sprinkler systems had lower point source emissions than did conventional drip systems, but we need to acquire datasets that will allow us to spatially model the microjet spray fertigation emissions before definitive statements can be made about total emissions quantities.

Materials and Methods:

GHG Annual Monitoring Measurements

To account for the seasonal, spatial and daily variations in GHG emissions (CO_2, N_2O and CH_4), requires intensive measurements over time and space. Soil GHG efflux of CO_2 and N_2O (and CH_4, not currently analyzed) have been monitored on a bi-weekly basis (since October 2007 until October of 2008), at a 20 hectare mixed variety almond orchard at the Nickels Soil Laboratory, Arbuckle, Colusa Co. and at a 984 acre site at Belridge, Kern Co. (from April of 2009 to the present). Monitoring at the Nickels Soil Laboratory site will resume in October of 2009 and continue until we have a full second season of GHG monitoring. Samples were taken from 18 locations throughout both orchards and covered areas managed by both surface drip and microjet sprinkler jet irrigation systems while at Belridge only microjet sprinkler was evaluated. In addition to locations situated in the “drip zone”, samples were also taken within the tractor rows in order to account for spatial variation within the orchard floor. Soil gas efflux samples for N_2O and CH_4 were measured using a closed chamber technique (Mosier, 1998), where chambers were sealed for 2 to 3 hours over which time four gas samples were taken using 20 cc evacuated gas vials. Samples were obtained between 11 a.m. and 3 p.m. to capture peak mid-day fluxes.

[ŧ] A carbon equivalent is defined as the estimated quantity of CO_2 in the atmosphere that would have the equivalent radiative warming potential (greenhouse gas potential) of one mass equivalent of CO_2, where the radiative warming potential of CO_2 is set to 1.0.

Spatial Constraints on GHG Emissions

For spatial variation we performed a proof of concept experiment during this funding period by taking two transects along the berm (planted row) and a second at 90° to the first transect and crossing in the center of the drip zone. Each transect had a total of $n = 7$ measurement positions, and was repeated on three independent drip zones. The two opposing 90° transects allowed us to develop empirical models (Gaussian fits) of flux across each transect that could then be used to generate probability density functions for each transect. These functions were then used to populate the cells for a three dimensional response plane. The two response planes will be used to spatially constrain fluxes in perennial crops systems receiving N through fertigation using conventional drip.

Smaller static chambers of 12.5 cm diameter are placed over temporary collars at the soil surface substantially reduces the time constant for emissions capture. Gas samples of 13 cc are removed from the chamber at 0, 30 and 90 minutes (or 0, 15 and 45 minutes depending on rates) and injected into evacuated 12 cc exetainers. N_2O is analyzed on the gas chromatograph (GC) using a Poropak Q Column (1.8 m, 80/100, 90ºC) with a ^{63}Ni electron capture detector. CH_4 is analyzed on the GC with a Poropak Q Column and a flame ionization detector (300ºC). Rates of N_2O (or CH_4) emissions are calculated according to:

$$J_{N2O} = d[N_2O]/dt * Vn/RA * P_a/P_s * T_a/T_s \qquad \text{eq 1}$$

where J is the apparent net flux of N_2O (or CH_4) from the soil surface (umol m^{-2} s^{-1}), $d[N_2O]/dt$ is the change in N_2O (or CH_4) concentration in the chamber over time, V is the chamber volume (L), P_a, P_s, T_a and T_s are ambient (a) and standard (s) atmospheric pressures (Pascals) and temperatures (Kelvin), R is the universal gas constant and A is the chamber area (m^2).

Diurnal Studies – Effect of Management Practices upon GHG Emissions

One of the primary issues in assessing carbon footprints of agricultural systems concerns the erratic spatial and temporal nature of soil N_2O emissions. In order to establish the seasonal and temporal variation in GHG emissions and to monitor the N_2O and CO_2 emissions events following application of nitrogen fertilizers and irrigation water ("fertigation"), we conducted several intense diurnal and week long studies.
The first diurnal experiment occurred in November 2007 to establish a winter baseline for the GHG emissions, when no management practices (e.g. irrigation) were occurring. This experiment occurred over 36 hours, where N_2O and $CO_{2,}$ along with soil moisture and temperature were measured every 2 and 3 hours (using the above methods, respectively) throughout the whole orchard, which included two types of irrigation systems, surface drip and micro-sprinkler jets. The intent of this approach was to allow us to apply 2-dimensional models to the fluxes in order to have more robust estimates for the whole orchard (both from areas where N is applied and alleys where N is not applied).

In an experiment in March 2008, we investigated the effects of the type of nitrogen fertilizer applied upon the release of N_2O via the microbial denitrification process. We carried out an intensive diurnal study on the microjet sprinkler irrigation system only, where approximately 50 lbs/acre nitrogen was added in the form of nitrate (NO_3^-). Measurements of N_2O and CO_2 occurred every 2 hours for the first 24 hours and then midday measurements were obtained for the next 7 days, with repeated measurements taken at midday on days 10, 21 and 24 after fertigation. Inorganic nitrogen (nitrate, nitrite and ammonium), total soil carbon to nitrogen ratios, soil moisture, temperature were obtained throughout the experiment.

A final experiment in April 2008 was conducted to ascertain the extent of GHG emission from a “normal” management fertilization practice, where approximately 60 lbs/acre of nitrogen in the form of urea nitrate (UN32), a commonly used fertilizer within the almond industry was applied to the whole orchard. Within this experiment both the micro-sprinkler and surface drip irrigation systems and their subsequent effects on N_2O and CO_2 emissions were investigated. Measurements of the gases along with ancillary data were obtained from midday measurements for 5 days following the fertigation event.

Soil Carbon Sequestration

Composite soil samples were taken to a depth of 15 cm from within the vicinity of the gas collars placed around the orchard before during and after irrigation in March and April 2008. Samples were dried and ground and have been sent off for total carbon and nitrogen analysis, as well as particle size analysis, results are pending.

Results and Discussion:

GHG Annual Monitoring Measurements

At this time we have approximately 12 months of monitoring data for three irrigation management schemes (conventional drip, microjet spray and subterranean drip) that encompass an entire growing season (October 2007 to October 2008) for the orchard at Nickels Soil Laboratory. We have 5 months monitoring observations for the almond orchard at Belridge under microjet spray and fertilization with Urea Ammonium Nitrate (UAN) and Calcium Ammonium Nitrate (CAN), **Figure 1**. These monitoring scenarios will be continued to the point where we are in possession of two full seasons of data for each management system.

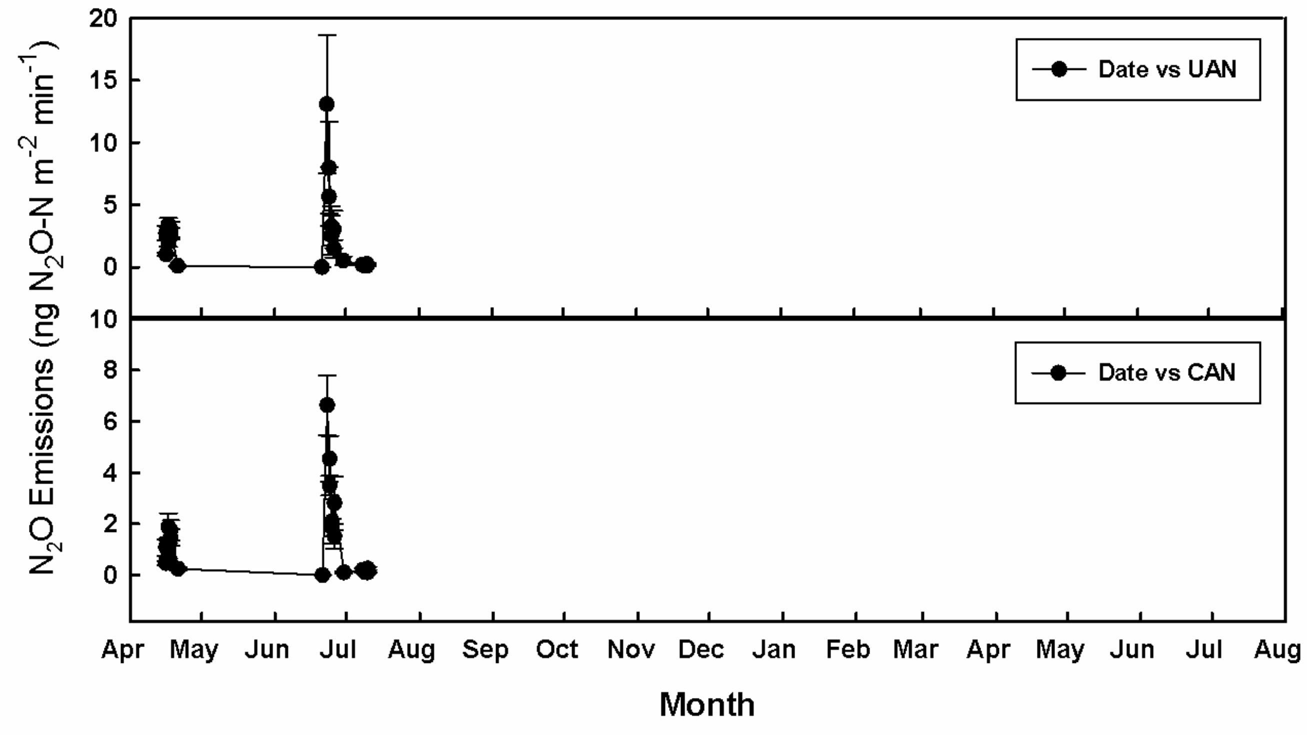


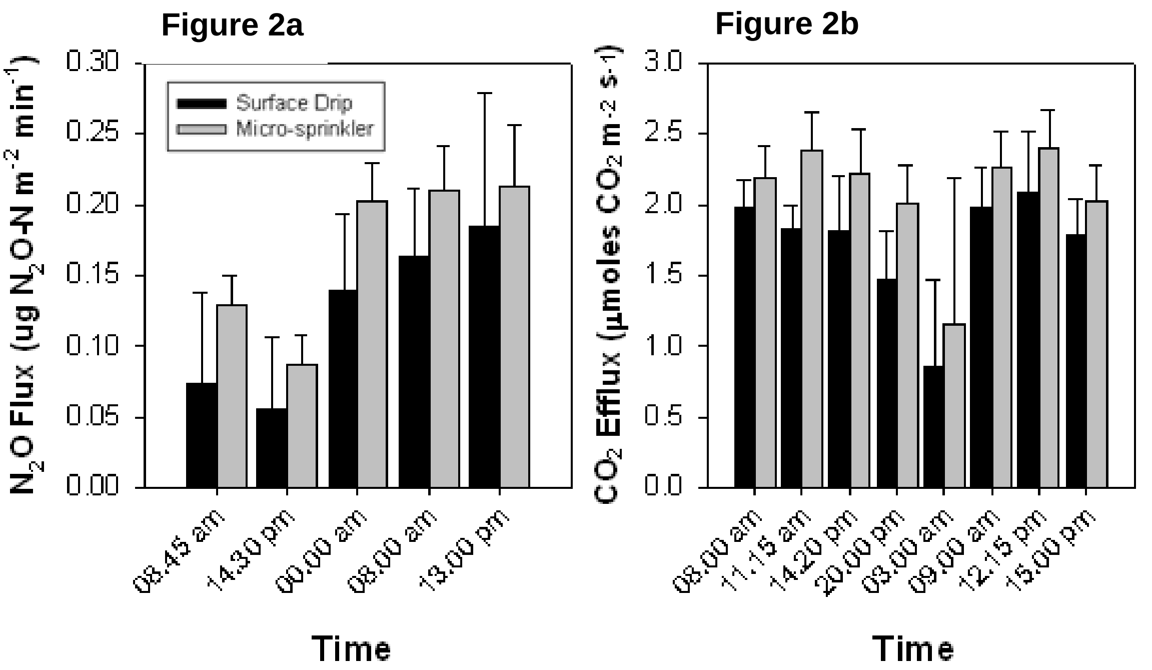
Figure 1: Shown are the means and standard errors for the first four months of emissions measurements obtained at the Belridge almond orchard. For each of the two sites being utilized in this investigation, two full seasons of emissions measurements will be acquired.

Precipitation regimes, irrigation and fertilizer applications are the key factors affecting N_2O emissions from soils. To gain insights into how the irrigation and nitrogen fertilization practices usually utilized within the almond industry affect GHG emissions, we conducted several experiments to investigate the extent of GHG emissions occurring under "normal" water and nitrogen management practices at the Nickels Soil Laboratory experimental orchard.

In an experiment in November 2007, measurements of CO_2 and N_2O were taken over a 36 hour period to investigate the diurnal effects on trace gas emissions as well as to look at the differences between two irrigation treatments (surface drip and micro-sprinkler) during a time when there were no management practices (e.g. irrigation or fertilization) occurring. **Table 1** shows the average soil temperature, soils moisture and the averages for both CO_2 and N_2O, for each of the two irrigation treatments over the whole experiment. Soil moisture was observed to be the same in both treatments, where soil temperature was marginally higher within the surface drip treatment compared to the micro-sprinkler treatment.

Table 1: Average soil parameters and gas fluxes over 36 hours for two irrigation treatments.

Irrigation Treatment	Average Soil T (°C)	Average Soil Moisture (%)	Average CO_2 (µmoles CO_2 m^{-2} s^{-1})	Average N_2O (µmoles N_2O m^{-2} s^{-1})
Surface Drip	15.43	11	1.72	0.19
Microspray	14.63	11	2.08	0.26



Figures 2 a & b: Diurnal soil N_2O emissions (a) and CO_2 efflux (b) over a 36 hour period in November 2007, within the surface drip (black bars) and micro-sprinkler (grey bars) irrigation treatments at the Nickels orchard. Error bars indicate standard error of the mean (n = 6).

Figure 2 shows that the micro-sprinkler irrigation treatment emitted higher quantities of N_2O and CO_2 on average throughout the entire 36 hour experiment compared to the surface drip treatment (**Table 1**). Like most biological processes, this difference is most likely due to differences in soil properties (e.g. soil texture, carbon content etc.) at each sampling site as well as the differences between the two irrigation systems in terms of spatial uniformity of water application. Further analysis of this data and future experiments to test for the spatial variability within the orchard are needed.

Figure 3a shows the flux of N_2O and soil moisture before and after the application of 50 lbs/acre nitrate fertilizer to the micro-sprinkler systems within the orchard. This fertilizer was used in order to ascertain the extent of N_2O emissions arising from the microbial process of denitrification as well as to start looking at the differences in emissions from the utilization of various forms of nitrogen fertilizers. Fluxes of N_2O are higher after the first two hours of fertigation and this corresponds also with the high soil moisture content after irrigation. After the first 24 hours, fluxes remain high and then start to return to background levels after the first week.

In **Figure 3b**, soil CO_2 efflux stays relatively stable throughout the course of the experiment and seems to not be affected by the application of the nitrogen fertilizer. A small diurnal influence can be seen where soil CO_2 efflux decreases when soil temperatures are lower at night and early morning, but these differences were not statistically significantly different.

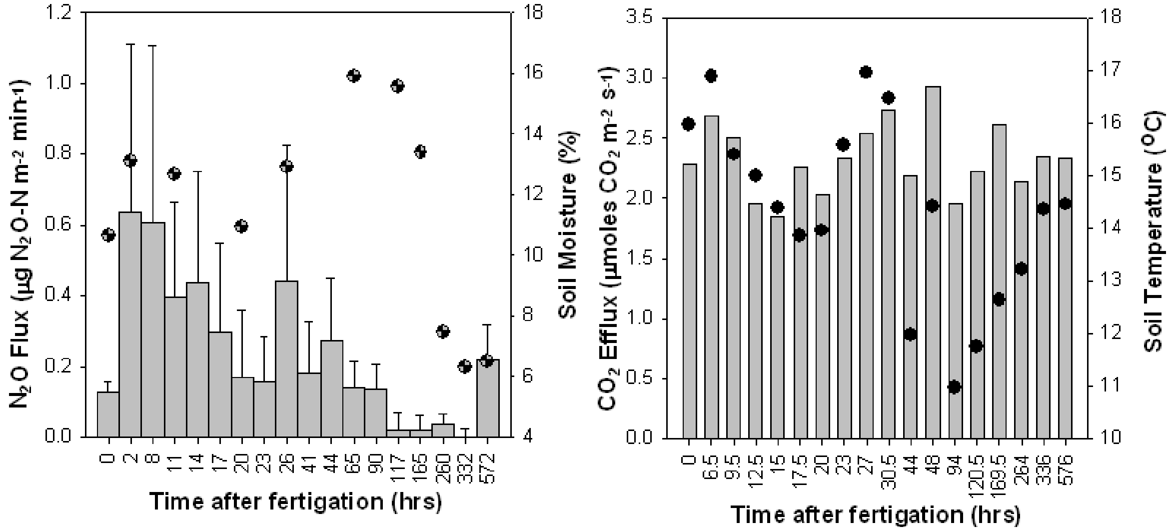


Figure 3a **Figure 3b**

Figure 3: (a) Soil N_2O emissions (grey bars) and soil moisture (black and white circles) and; (**b)** CO_2 efflux (grey bars) and soil temperature (black circles) from the micro-sprinkler irrigation treatment at the Nickels orchard over a 24 day period after the application of 50 lbs/acre nitrate. Error bars indicate standard error of the mean (n = 3).

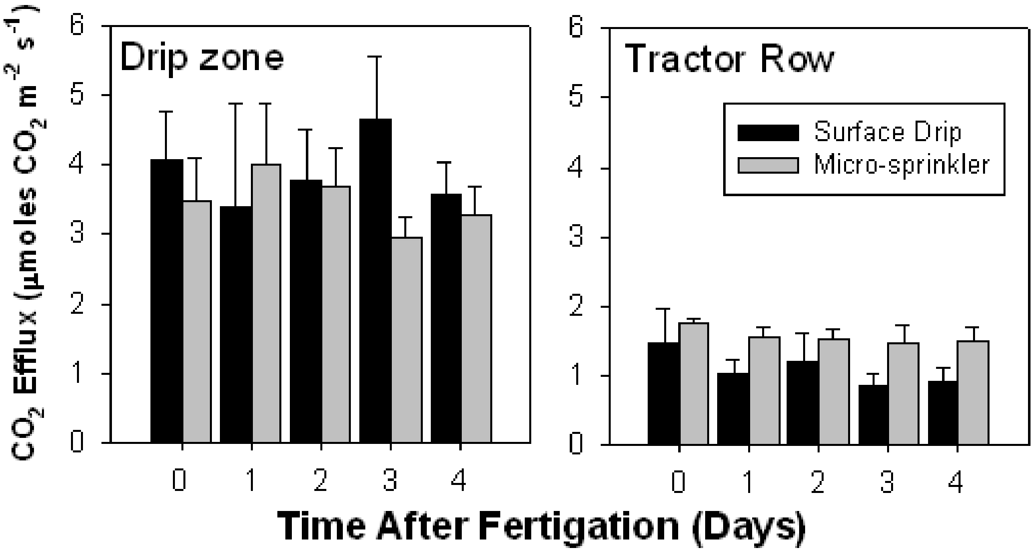


Figure 4a **Figure 4b**

Figure 4: Soil CO_2 efflux from surface drip (black columns) and micro-sprinkler (grey columns) irrigation systems in a four day experiment before, during, and after the application of 60 lbs/acre urea nitrate. Samples were obtained from around the Nickels orchard within the drip zone **(a)** and within the tractor row **(b).** Error bars indicate standard error of the mean (n = 4).

Soil CO_2 efflux was not influenced by the application of nitrogen, however CO_2 efflux observed within the drip zone areas was observed to be almost double the CO_2 efflux observed within the tractor rows. This may be due to differences in soil moisture content, soil temperature and spatial variability around the orchard itself, as the tractor rows receive little or no water from irrigation. For both sets of data, the differences between the irrigation treatments are not statistically significant.

Figure 5 shows the soil N_2O emissions from surface drip (black columns) and micro-sprinkler (grey columns) irrigation systems after the application of 60 lbs/acre urea nitrate (UN32). Emissions from the surface drip irrigation observed within the drip zone are nearly one order of magnitude higher compared to the relatively low emissions exhibited by the micro-sprinkler irrigation system. This may be due to an over saturation of the micro-sprinkler system due to the high moisture content compared to the moisture content of the surface drip system (**Table 2**). Within the tractor row, soil N_2O emissions are extremely low and are near ambient concentrations. The micro-sprinkler irrigation system samples are higher than the surface drip. Again this could be due to a higher moisture content as the micro-sprinkler systems cover a wider area with water compared to the surface drip.

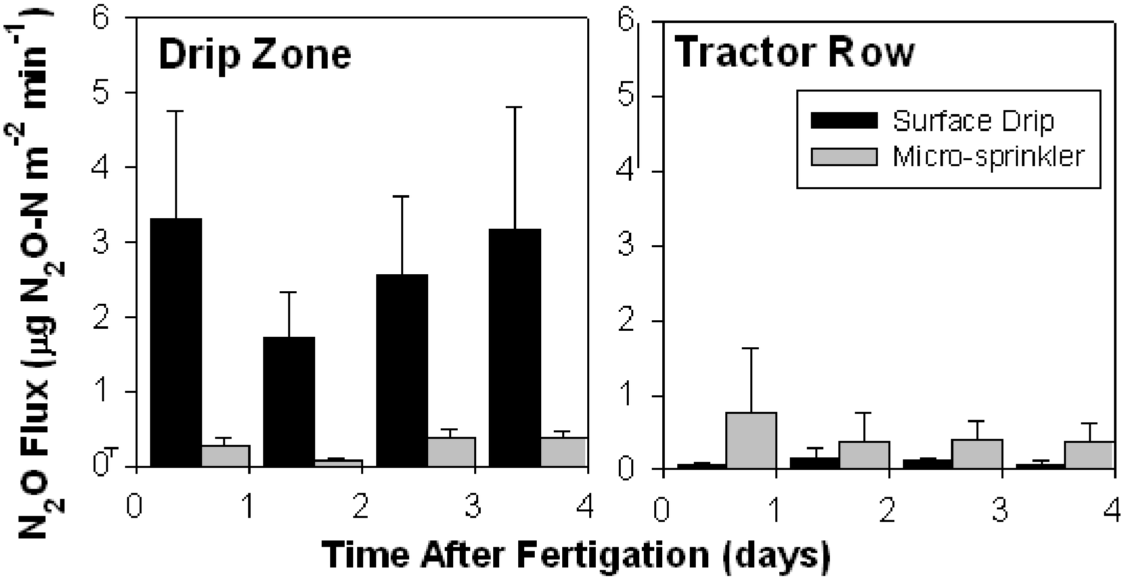


Figure 5a **Figure 5b**

Figure 5: Soil N_2O emissions from surface drip (black columns) and micro-sprinkler (grey columns) irrigation systems in a four day experiment before, during and after the application of 60 lbs/acre urea nitrate. Samples were obtained from around the Nickels orchard within the drip zone **(a)** and within the tractor row (b). Error bars indicate standard error of the mean (n = 3).

Table 2: Soil moisture and gas fluxes for CO_2 and N_2O from three experiments investigating the effects of irrigation and N fertilization upon gas emissions at Nickels Soil Laboratory. Data is taken from drip zone region only for the two irrigation treatments.

Treatment	**Micro-Sprinkler**			**Surface Drip**		
	CO_2 (µmoles m^{-2} s^{-1})	**N_2O** (µmoles N m^{-2} s^{-1})	θ_v%	**CO_2** (µmoles m^{-2} s^{-1})	**N_2O** (µmoles N m^{-2} s^{-1})	θ_v%
Winter Baseline	2.08	0.26	11	1.72	0.19	11
50lbs N as NO_3^-	2.36	0.32	13	nd	nd	nd
60 lbs N UN32	3.47	0.26	15	3.89	2.37	7

During the previous funding period we performed a proof of concept experiment by taking two transects along the berm (planted row) and a second at 90° to the first transect and crossing in the center of the drip zone. Each transect had a total of n = 7 measurement positions, that were repeated on three independent drip zones. The two opposing 90° transects allowed us to develop empirical models (Gaussian fits) of flux across each transect that could then be used to generate probability density functions for each transect. These functions were then used to populate the cells for the response planes shown in **Figure 6**. The two response planes will be used to spatially constrain fluxes in perennial crops systems receiving N through fertirrigation using conventional drip. The temporal component consists of the response shown in left versus the right panel.

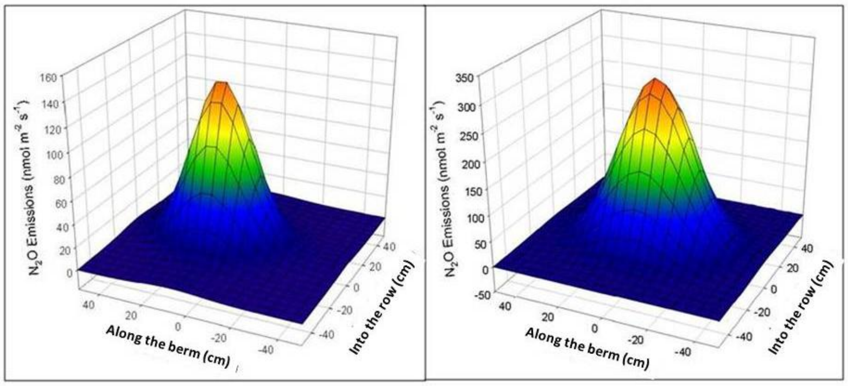


Figure 6: Spatial variation in N_2O emissions around a drip zone following an application of the equivalent of 40 lbs N per acre. The models were developed using probability density functions based on N_2O flux transects (n = 7) were taken along the berm and into the row. The left panel is 12 h following the fertigation event and the right panel at peak temperatures, 18h following the event.

Conclusions:

There was great variability between both irrigation systems we examined, and this may be due to many different factors such as soil physical properties variation in the orchard, seasonal effects of temperature change in addition to the different management practices. To try and constrain the variation further analysis is needed concerning targeting fertigation events and to understand the underlying processes within the orchard system relative to GHG emissions and carbon sequestration processes and the assemblage of an annual GHG budget. We have made substantial progress in this respect and are now in possession of sufficient data to initiate exercises in conjunction with modeling efforts that can be used to examine a broader range of management scenarios.

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Recent Publications:

Steenwerth, K.L., D.L. Pierce, E.A. Carlisle, R.G.M. Spencer and D.R. Smart (2009) Tillage disturbance and precipitation affect soil respiration under Mediterranean conditions. Soil Science Society of America Journal (in press)

Smart, D.R., E.C. Suddick, K.M. Scow, P.H. Brown, T. DeJong (2009) An Assessment of the Carbon Sequestration Opportunities and Greenhouse Gas Emissions Attenuation by Almond Orchards in California. (in review)