Constraining Greenhouse Gas Emissions from Almond Orchards for Two Nitrogen Fertilizer Sources and Three Microirrigation Systems

Project No.: **10-AIR2-Smart**

Project Leader: David R. Smart
Associate Professor
Department of Viticulture and Enology
UC Davis
One Shields Avenue
Davis, CA 95616
drsmart@ucdavis.edu

Project Personnel: Maria Mar Alsina-Marti, Post Doctoral Researcher, UC Davis
Daniel L. Schellenberg and Christine M. Stockert, Graduate Student Researchers, UC Davis

Project Cooperators:
Patrick Brown, Saiful Muhammad, UC Davis
Blake Sanden, UCCE – Bakersfield
John Edstrom, UCCE – Colusa
Paramount Farming Company
Nickels Soil Laboratory

Objectives:

Nitrogen mobilization (offsite transport of reactive forms of N, including NH_4^+, NO_2^-, NO_3^- plus the gaseous forms of NH_3, N_2O, and NO_x) has become an important environmental concern of State and Federal Regulatory organizations. This concern comes from passage of the California Global Warming Solutions Act, Assembly Bill 32 in June of 2006 (AB 32), and the US EPA's recent endangerment finding for GHGs such as CO_2, N_2O and CH_4 (http://www.epa.gov/climatechange/). This finding subjects these gases to scrutiny under the Clean Air Act. The current project represents a merging of two previous projects whose overarching objective is to constrain (quantify accurately) nitrogen use efficiency of almond (NUE), here defined as enhancing nitrogen retention in orchards and fostering economically favorable production, while minimizing offsite transport of reactive forms of N. The project integrates with objectives of 7 other principal investigators through a highly coordinated investigation under the direction of Dr. Patrick Brown. The project highlights the enhancement of sustainable practices through better understanding of how irrigation and fertigation practices influence N mobilization. Among a number of objectives being pursued under this investigation, some of the more pertinent to improving sustainable practices include:

1) To compare N_2O emissions from two different forms of nitrogen (N) fertilizer, urea ammonium nitrate (UAN) and calcium ammonium nitrate (CAN).
2) To evaluate seasonal variability of N_2O emissions before and after fertilizer application and integrate observations for seasonal comparison.
3) To identify factors such as water-filled pore space, soil temperature, inorganic N concentration and pH to develop a greater understanding of the controls of N_2O emissions from almond orchards.
4) To develop spatially explicit models of N_2O emissions for improved quantification of drip and microjet sprinkler fertigation applications in almond orchards.
5) To estimate orchard fluxes of reactive N (NH_4^+, NO_2^-, NO_3^-, NH_3, and N_2O) and movement of N into leaves and fruit using an isotopic tracer approach to better understand NUE at the orchard scale.

Deliverables from Objectives:

Overall, we have documented that N_2O emissions are equal to or less than half that attributable to IPCC assessment values (IPCC, 2007). In addition:

1) We have found that N_2O emissions from calcium ammonium nitrate fertilizer (CAN), is substantially less than from urea ammonium nitrate (UAN) fertilizer.
2) We have found that N_2O emissions were diminished when microjet sprinklers were utilized as the fertigation delivery system as compared to drip irrigation.
3) We've discovered at least one scenario where methane was apparently being absorbed (oxidized) by methanotrophic microorganisms in orchard soils. With a climatic warming potential 24 times greater than CO_2, methane oxidation offsets GHG production and offers mitigation potential to be investigated.
4) We successfully traced 15-nitrogen through root pathways within 36 hours, enriched the leaf canopy and the 2010 crop and continue to monitor four trees.

Interpretive Summary:

Our investigation is acquiring baseline rates of nitrous oxide (N_2O) emissions for fertilization rates of almond of approximately 200 to 235 units N acre^{-1}. Nitrous oxide emissions followed distinct patterns after fertilizer applications and according to season (soil and ambient temperature), soil moisture and soil mineral N concentrations. Peak emissions occurred between 11 and 60 hours after fertilizer application depending on season. This appeared to be related to the duration of time where water filled pore space (WFPS) in soils exceeded 50%, and points to the real possibility of modifying water and fertilizer N application to establish mitigation measures or possible off-sets to diminish N_2O emissions. In most cases we have documented that N_2O emissions per unit of N fertilizer applied to California almonds were substantially less than the amount estimated by emission factors (EFs) utilized for greenhouse gas emissions assessments (IPCC, 2007). We continue in a concerted attempt to directly communicate these favorable results to the California Air Resources Board (CARB).

Two potential management practices were identified. Our preliminary results have indicated that N_2O emissions are generally less for calcium ammonium nitrate fertilizer

(CAN) as the N-source, as compared with urea ammonium nitrate (UAN). The method of delivery in those experiments was microjet sprinkler irrigation which we have documented as having lower emissions amounts. During summer, peak N_2O emissions within 10-60 h following UAN applications were significantly greater than emissions from CAN applications ($p < 0.0001$). This result was unexpected in as much as NO_3^- is the main substrate for denitrification and CAN contains more NO_3^- per unit fertilizer N than UAN. Greater emissions from UAN indicated more information is needed on nitrification rates, and emissions of N_2O from the nitrification pathway. This is because UAN contains higher quantities of NH_4^+, some of which is released from urea hydrolysis. Our investigation of CAN versus UAN only evaluated microjet sprinkler irrigation and further studies to evaluate drip irrigation delivery ought to be considered.

In another unexpected development, we found that N_2O emissions were less under microjet spray fertigation when compared to conventional drip fertigation. We have verified this result by monitoring emissions patterns over the course of an entire season, quantifying the amount of N_2O using intensive spatial and temporal sampling. We used multiple sampling points to capture the distribution of emissions and then scale it up to the orchard level over time. Using a ^{15}N non-radioactive isotope tracer has further verified these findings. How mineral-N (NH_4^+ and NO_3^-,) and WFPS effect emissions were discerned using multi-variate analyses. We have found most variation in N_2O emission is explained by the percentage of water filled pore space greater than approximately 50% ($R^2 = 0.40$, Smart et al. 2011) whereas total mineral N in the soil (fertilizer) was less important. Microjet sprinklers apply N and water to a more extensive area of the orchard floor, but our results indicated the surface soil zone, where microbial denitrification activity is high, dries more rapidly than the zone of water and N applied by drip which infiltrates to deeper horizons in the soil profile.

We have carried out these experiments in conjunction with intensive monitoring of yields in cooperation with the Almond Board of California and a USDA Specialty Crops Research Initiative grant (USDA SCRI), and have documented that yields are not adversely affected by microjet spray versus drip micro-irrigation systems. This alliance is extremely important because the range of N applied (125 to 350 lbs. per acre) allows us to calculate a yield based global warming potential and thus weights gas emissions against yield opportunity loss.

Materials and Methods:

Seasonal N_2O Emissions

My program currently has two separate experiments examining N mobilization in almond orchards. The first is part of a larger effort to study nitrogen use efficiency by almond. The project is funded through the USDA Specialty Crops Research Initiative under the direction of Patrick Brown and is carried out in Belridge Orchard near Lost Hills California. The second is conducted at the UC Davis Nickel Soils Laboratory near Arbuckle California. Both experiments are represented by complete randomized blocks design for the variables of drip, sprinkler, CAN and UAN treatments. The N application rates range from 200 (UAN versus CAN) to 210 lbs acre^{-1} per year fertigated as individual events of from 40 to 60 lbs acre^{-1}.

My laboratory has more than a decade of experience in measuring and quantifying fluxes of reactive forms of nitrogen (N) and quantifying their mobilization in agricultural and other settings (eg. Smart et al. 1999; Smart and Bloom, 2001; Stark et al. 2002; Bloom et al. 2002; Smart and Peñuelas, 2005; Carlisle et al. 2006; Volder et al. 2009; Steenwerth et al. 2009; Smart et al. 2010; Suddick et al. 2010; Suddick et al. 2011; Smart et al. 2011). Included in the reactive N species we measure are nitrate (NO_3^-), nitrite (NO_2^-), ammonia gas (NH_3), ammonium (NH_4^+), nitrous oxide gas (N_2O) and the 'nox' species of gases (NO_x) which includes nitric oxide (NO) and nitrogen dioxide (NO_2). In addition to these gases, we are also accomplished in the quantification of CO_2 and water vapor exchanges in the soil-plant-atmosphere continuum. We scale from the leaf level up to the level of whole canopies like orchards, either directly or using modeling exercises. Our approaches include soil surface and leaf level exchanges of the gases and boundary layer micrometeorological measurements. For the soluble ionic forms of N (NO_3^-, NO_2^-, NH_4^+) and the soil microbial N transformations of nitrification and denitrification that produce and consume them. Finally, we employ tracers of, or 'natural abundance' levels of, ^{13}C and ^{15}N in this work to quantify biogeochemical process rates, like that of orchard soil N-mineralization and absorption and assimilation of N by trees, and to identify competitive relationships between plant roots and microbial organisms in the soil.

For this report, gas emissions sampling for N_2O and soil sampling for moisture content, NH_4^+ and NO_3^- was conducted during the primary phenological stages of almond, eg. spur growth and nut fill, thought to correspond to periods of highest N demand. We apply fertilizer N in a targeted manner at these stages to foster tree competition for N. We targeted our gas measurements for periods when soil and ambient temperatures and soil moisture would be favorable to nitrification and denitrification, the two microbial processes that produce N_2O. We refer to these stages and periods of time as Spring, Summer, Post Harvest and Winter, in general, noting that the periods of highest N-demand are Spring and Summer. The specific time periods were: Winter, Nov. 1-Jan. 31; Spring, Feb. 1-April 30; Summer, May 1-August 31 and Post Harvest, harvest date - Oct. 31 (Lopus et al., 2010). The investigations were conducted at Paramount Farming Company's Belridge Almond Ranch near Lost Hills, CA on a sandy loam (sandy-clay) soil and at the Nickels Soil Laboratory (sandy gravelly loam) in Arbuckle California. The timing for all cultural practices was coordinated in close collaboration with University of California Cooperative Extension Specialist Blake Sanden or Paramount personnel, including water and nitrogen applications.

The experiments we conducted were carried out in fully replicated randomized blocks experimental designs. In this way all data was subjected to the rigors of analysis of variance using Statistical Analysis Systems (SAS Cary, NC). Data was transformed when necessary to meet the general assumption of a normal (Gaussian) distribution of data. Modeling exercises were used at the spatial scale to insure that the calculation of gas fluxes at the orchard scale were as accurate as feasible.

Spatial Modeling of N_2O Emissions

The main objective of this experiment was to assess if the total N_2O emitted per hectare of orchard was substantially influenced by the micro-irrigation system used. To achieve this objective, N_2O emissions were monitored after fertigation events and over an entire season using a series of transects in treatments utilizing microjet sprinkler versus drip irrigation as variables (**Figure 1**).

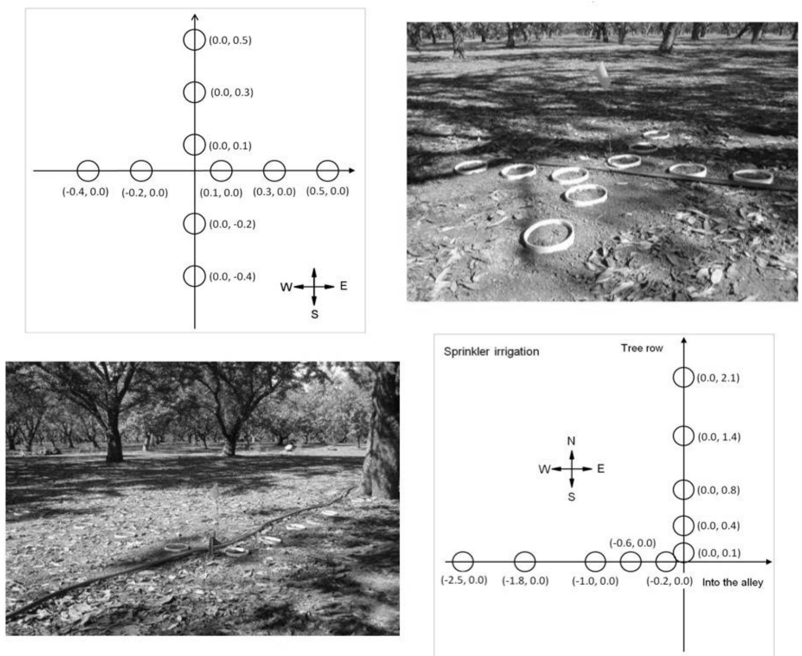

Figure 1. Collar distribution (scheme and picture) for sprinkler irrigation and for drip irrigation. Pictures correspond to the collars installed in Nickels soil lab Almond Orchard in Arbuckle, CA.

Shown in **Figure 2** are examples of micro-scale spatial modeling of emissions around drip and microjet sprinkler systems during an individual fertigation application of N at a rate of 30 lbs of N $acre^{-1}$ as CAN 17. These models provide the basis for scaling emissions to the orchard level using exercises that divide the orchard into areas with extremely low emissions (e.g. alleyways) and areas with relatively high emissions (the fertigation zone).

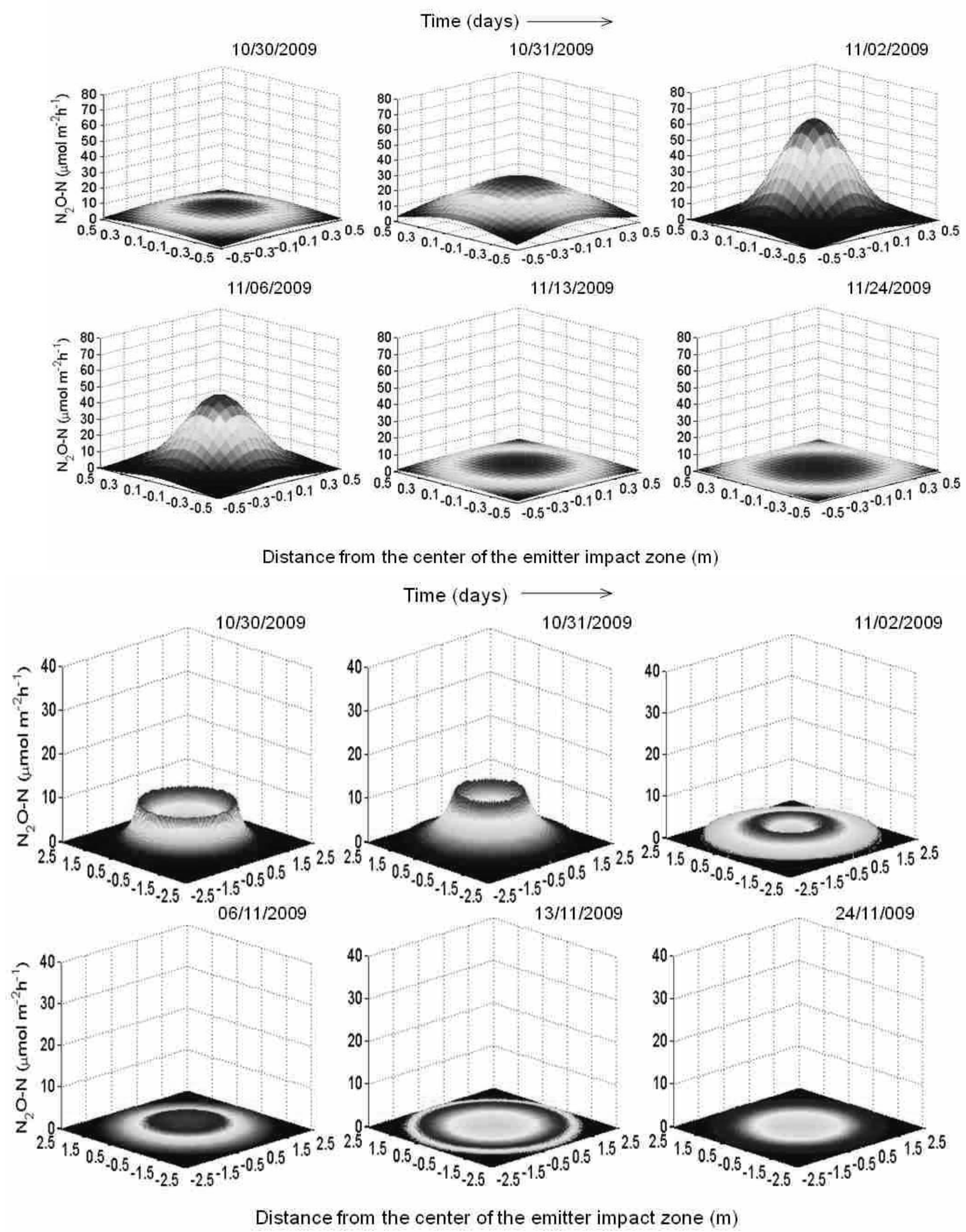

Figure 2. Distribution of N_2O emissions (μmol m^{-2} h^{-1}) under a drip emitter (top panels) and a microjet sprinkler (lower panels), following fertigation events of 30 lbs $acre^{-1}$ as CAN 17 in an almond orchard. The distributions of emissions shown were derived from three-dimensional fits of the Gaussian distribution (upper panels) and from fits of functions defined in two stages, a second degree polynomial and an exponential decay function (lower panels).

Results and Discussion:

Spatial Distribution of N_2O Emissions around Water Emitters

In order to better quantify soil generated N_2O around emitters, we designated a circular area of 1 m of diameter for drippers and of 5 m diameter for stationary microjet sprinklers. In three different trees (n = 3) for each of the irrigation systems we established two transects forming axes crossing at the drip or sprinkler irrigation emitter impact zone which was designated as the origin (0,0). One transect (N-S, y-ordinate) was established parallel to and directly in the tree row, and the other (E-W, x-ordinate) perpendicular to the tree row and into the alley **(Figure 1**). In each of these transects we determined 5 positions where soil N_2O flux was sampled. These 10 points per site were used to determine the N_2O emission distribution around the sprinkler or drip emitter. Drip irrigation showed a peak of emission in the center (emitter situation) followed by a rapid decline as the distance from the emitter increased, reaching values close to zero at distances of about 1 m from the center (**Figure 1 top panels**). In contrast to drip, sprinkler distribution we observed peak of emissions at a distance around 1 m from the center of the emitter and then it decreased exponentially until values close to zero were reached at distances of 2.5 – 3 m from the emitter (**Figure 2 bottom panels**).

Progress on Developing Comprehensive N_2O Emissions

Our results have indicated that N_2O emissions from almond orchards occur after fertilizer applications and subsequent irrigations (see **Figures 3 and 4**). Our results confirm the requirement to focus intensive measurements after fertilizer applications to accurately quantify emissions and that mitigation efforts will have to focus on nitrogen use efficiency (NUE, here defined as N acquired by orchard trees versus that mobilized as reactive N). Since multiple microbial processes contribute to the production of N_2O, past work has demonstrated equal contributions of nitrification and denitrification to total N_2O emissions following fertilization (Panek et al., 2000). Few measurements exist for microirrigated crops in the arid West of North America. Our work demonstrates a growing understanding of how N fertigation can act to mitigate emissions. In this case, the documented emissions were substantially less (**Table 1**) than estimated using emissions factors (EF_{N_2O}, at 1%, IPCC 2007) developed through exhaustive examination of the literature (Boumann et al. 2002).

Table 1. Seasonal N_2O emissions (lbs acre^{-1}), fraction emitted as N_2O-N (FE_{Calif}) and CO_2-equivalents (Global Warming Potential cf CO_2) for two different fertilizers, urea ammonium nitrate (UAN) and calcium ammonium nitrate (CAN), and three methods of N delivery (conventional surface drip, microjet sprinkler and subterranean drip, data not shown). Data are from 2 to 3 seasons with fertilizer applications of from 200 to 210 units of N acre^{-1}. Statistical significance at $P \leq 0.05$ indicated that CAN and microjet delivery systems had significantly lower emissions.

Crop	Soil Texture	Management	Units N (lbs ac^{-1})	*FE_{Calif}	N_2O-N (lbs acre^{-1} y^{-1})	¥GWP-equivalents (lbs CO_2 acre^{-1} y^{-1})
Almond	Sandy Loam	CAN	200	0.28%	0.45 ± 0.16	134 ± 48
Almond	Sandy Loam	UAN	200	0.48%	0.72 ± 0.22	215 ± 66
Almond	Sandy Clay Loam	Surface Drip	210	0.63%	1.32 ± 0.18	393 ± 54
Almond	Sandy Clay Loam	Microjet	210	0.25%	0.53 ± 0.10	158 ± 30
Almond	Sandy Clay Loam	Buried Drip	210	–	–	–

*FE = apparent fraction of fertilizer N emitted as N_2O-N.
¥GWP = global warming potential, lbs CO_2-equivalents using IPCC (2007) conversion factor of 300.

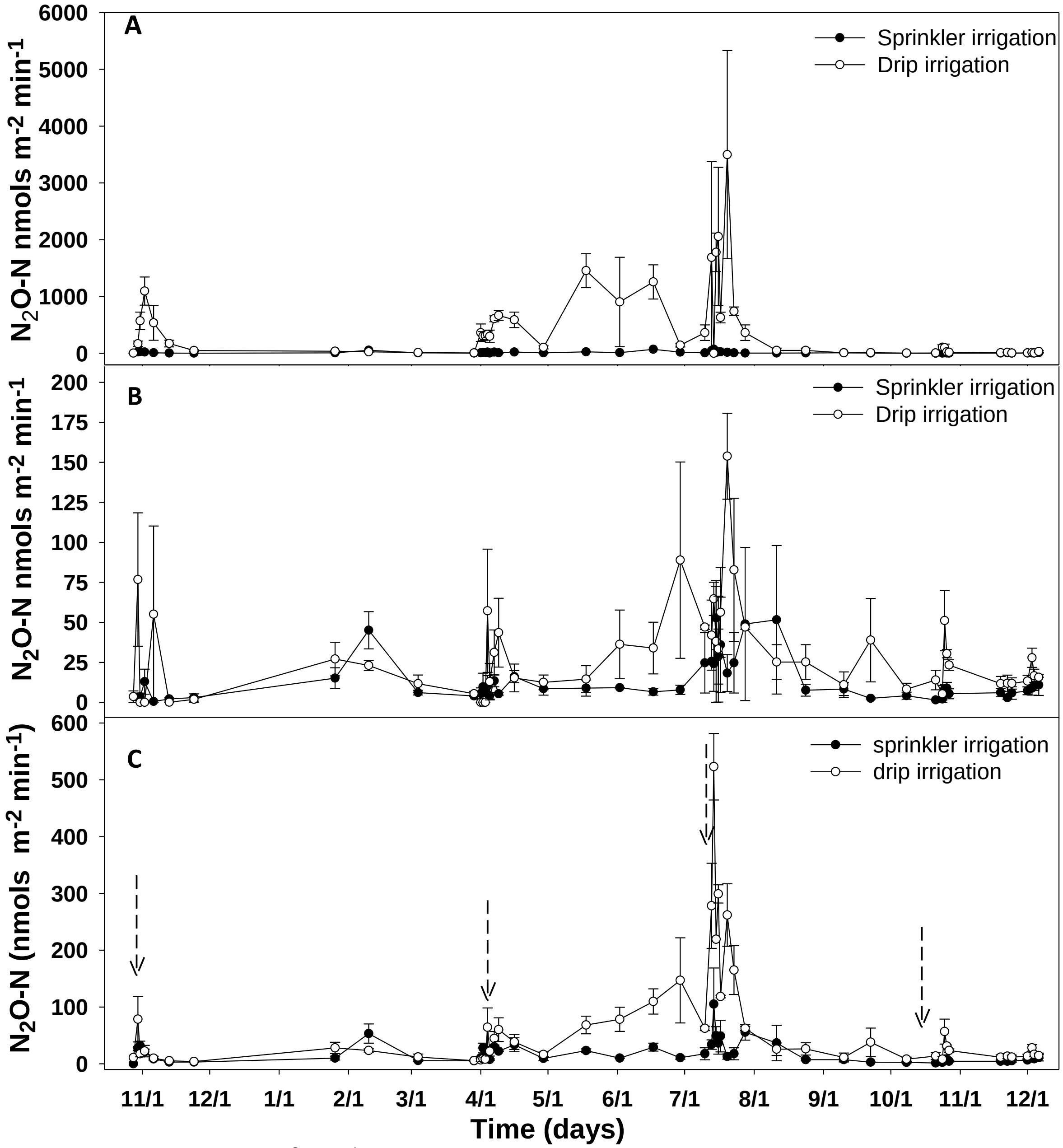

Figure 3: N_2O flux (nmol m^{-2} min^{-1}) measured in the wet up area under microjet sprinklers and drip emitters (A), in the dry area outside the wet-up zone (B) and in the driveway between the rows (C). Shown are the instantaneous rates of N_2O-N emission over the course of one season. Arrows represent dates when fertigations occurred.

For micro-irrigation systems (**drip versus microjet sprinkler**, **Figure 2**), water distribution patterns are known by manufacturers to follow specific patterns. To some extent N_2O emissions patterns may be spatially related to these delivery systems in as much as they influence soil water content and fertilizer distribution. Our data have indicated a relation between soil water and N_2O emissions. Other parameters that drive emissions, like NH_4^+ and NO_3^- concentration in soils were less important in influencing N_2O emissions. In spite of this, the application of fluid fertilizers was the primary event that resulted in N_2O emissions (**Figure 3 and 4**). From the modeled distribution of N2O emissions in each of the irrigation systems, we calculated the total amount of N_2O emitted per unit of soil surface over time and extrapolated it to the orchard scale. In so doing, we obtained the total mass of N as N_2O emitted per hectare during each event related increase in emissions. We monitored N_2O as described during one week to one month after each fertigation event (CAN 17, 30 lbs acre^{-1}). The instantaneous rates measured around the emitter (**Figure 3A**) were scaled to the orchard level using number of emitters per hectare. The instantaneous N_2O emissions rates (**Figure 3B**) measured in the alleyways were scaled up by alley area. The integrated totals of both these areas indicated that drip irrigation/fertigation emitted more N_2O-N than microjet sprinkler systems during the season (**Figure 3C** and **Table 2**).The maximum instantaneous rates of N_2O emission corresponded to levels exceeding 500 nmol N_2O-N m^{-2} min^{-1} and 100 nmols N_2O-N m^{-2} min^{-1} for drip irrigation and sprinkler irrigation, respectively.

For CAN and UAN, N_2O emissions after fertilizer applications followed distinct patterns according to season. During spring, N_2O emissions peaked after 60 hours following an application of 40 lbs N acre^{-1} and were not statistically significant different among treatments. In late spring, following a fertigated N application of 60 lbs N acre^{-1}, N_2O emissions peaked after 25 hours. During summer fertigation (60 lbs N acre^{-1}) N_2O emissions peaked after 10 hours and significantly greater fluxes were observed from UAN compared to CAN (p<0.0001). For post harvest N applications, peak N_2O emissions were observed approximately 60 hours following N addition (**Figure 4**). Our observations are supported by reports from different geographical regions where seasonal variability of N_2O emissions in relation to fertilizer management practice have been observed (Venterea et al., 2010; Verma et al., 2006).

Table 2: N_2O-N emissions (g N_2O-N ha^{-1}) during four fertigation events from Fall of 2009 to Fall 2010. Each value for N_2O-N represents the numeric integration of the measured instantaneous emissions (g N_2O-N m^{-2} min^{-1}) over space and time.

Seasor	Months	N (lbs/acre^{-1})	Fertilizer	Number of Days	N_2O-N (kg/ha) Sprinkler (mean±se)	Drip (mean±se)	
Fall	Oct-Nov	30	CAN 17	27	0.03 ± 0.04	0.07 ± 0.04	n.s.
Spring	Mar-Apr	50	CAN 17	31	0.09 ±0.01	0.14 ± 0.02	p<0.05
Summer	July-Aug	50	UAN 32	83	0.27 ± 0.08	10.17 ± 0.16	p<0.05
Fall	Oct-Nov	30	UAN 32	29	0.02 ± 0.01	0.08 ± 0.02	p<0.05

During and immediately following fertigation, soil WFPS and soil mineral nitrogen concentrations increase, and this resulted in a dramatic increase in N_2O emissions above baseline levels. As soon as fertigation ceased, a relaxation of emissions followed a decline in WFPS and soil mineral-N (**Figure 5**). Similar patterns were evident in other studies of both annual and perennial crops (Liu et al. 2010; Sauer et al. 2009)

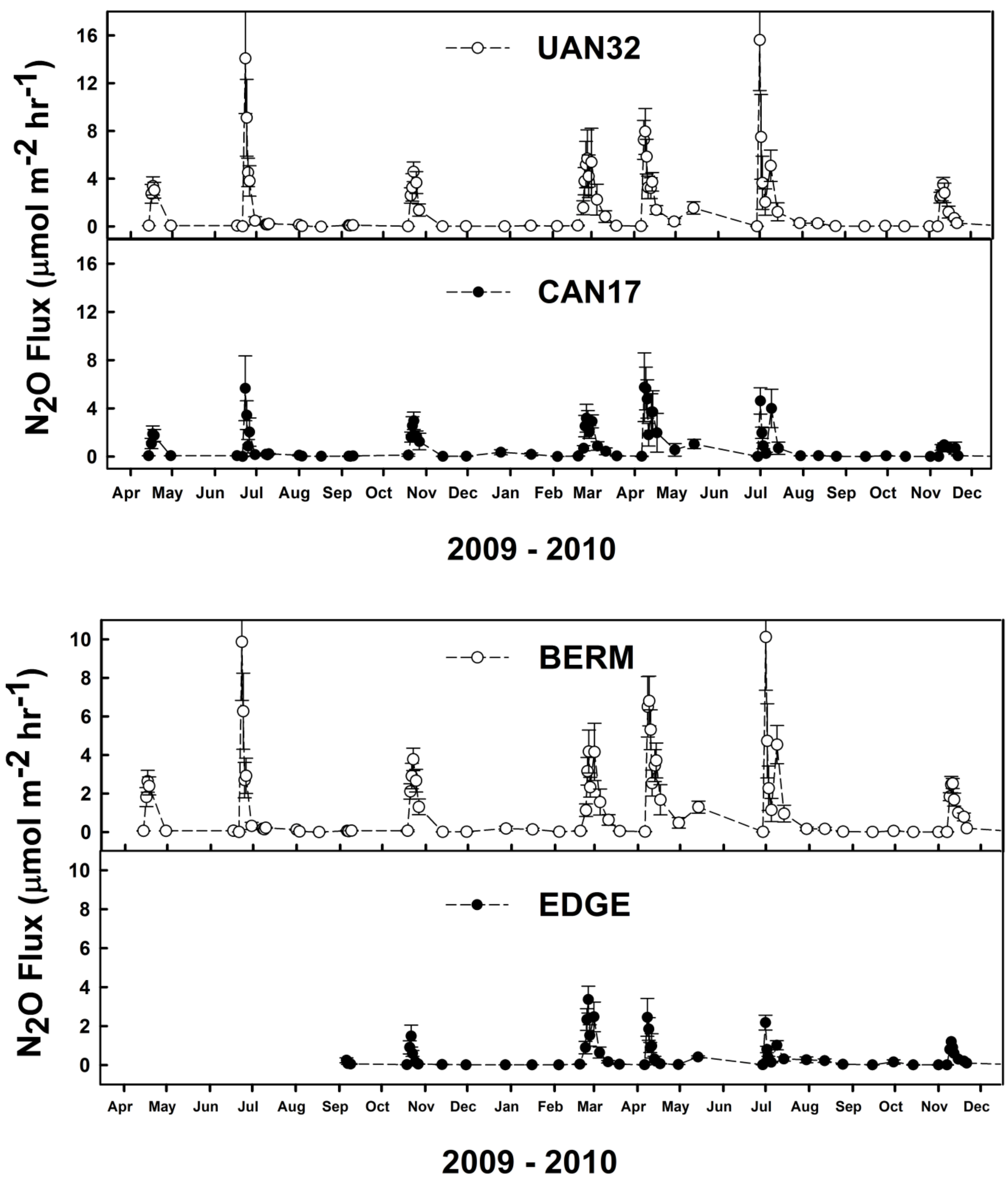

Figure 4. N_2O flux (μmol m^{-2} h^{-1}) for urea ammonium nitrate (UAN32) versus calcium ammonium nitrate (CAN17). Shown in the upper panels are the total instantaneous emissions for UAN32 and CAN17 during the 2009-2010 seasons. The two lower panels show emissions from within the microspinkler fertigated area (berm) versus the area in the driveway between rows where some edge effects occur for wet-up events (fertigation). The orchard is treated as having these two areas for quantifying total emissions (see Smart et al. 2011).

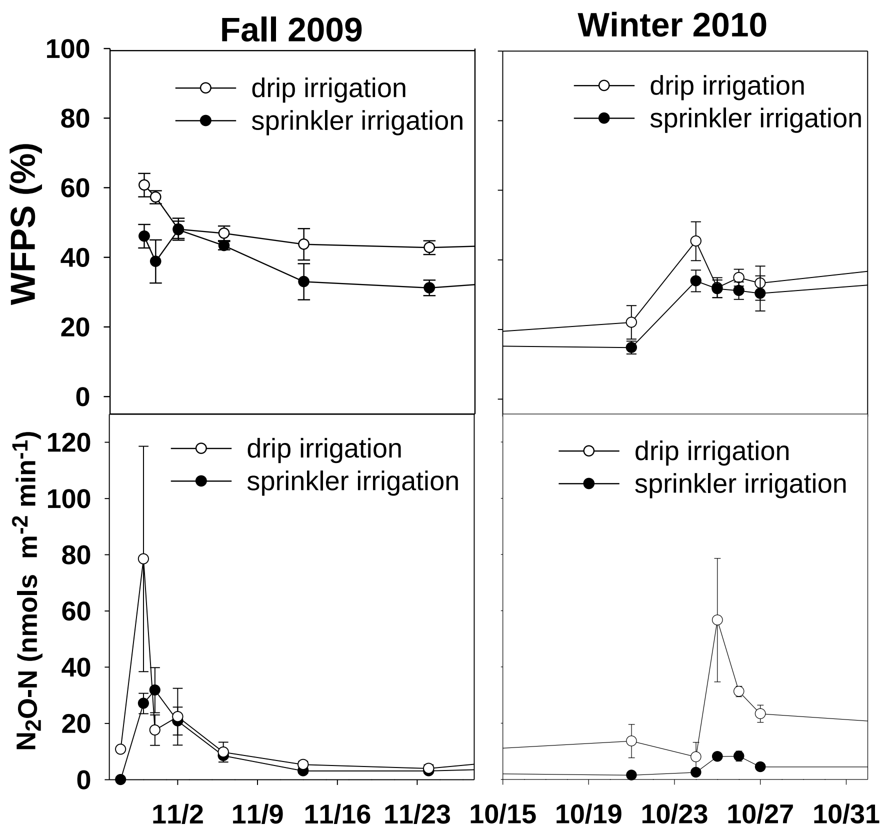

Figure 5: Average water filled pore space (WFPS, upper panels) measured in the area around the drip emitter or sprinkler, and N_2O flux (bottom panels). Shown are two fertigation events for two fertigation events at Nickels Soils Laboratoy near Arbuckle, California. Shown are the instantaneous rates of N_2O-N emission (nmol N_2O-N m^{-2} min^{-1}) over approximately three weeks during and following the fertigation event.

Following the stepwise regression procedure (SAS Cary, NC), we found that both WFPS ($p < 0.01$) and soil mineral N ($p < 0.01$) were significant soil variables that helped explain N_2O emissions during fertigation. In contrast, soil temperature was excluded from the regression since it showed no significant relation with soil N_2O flux ($p = 0.66$) (**Table 3**). Irrigation following fertilization appeared to be another important consideration since increased WFPS when mineral-N was still available stimulated N2O emissions. When soil mineral-N seems to be a limiting factor after successive irrigations. This result is supported by the coefficients from multiple regressions (**Table 4**) where soil mineral content explains a greater proportion of N_2O emissions as compared to WFPS (**Table 3**).

Table 3. – Coefficients, significance (*p*) and R^2 values for single regression. Water-filled pore space (WFPS) and soil mineral N (N_m) were significant parameters to predict N_2O emission.

Soil parameter	Single regression		
	Value	*p*	R^2 value
Water Filled Pore Space (%)	0.06	*<0.001*	0.20
Soil mineral N (NH_4^+ & NO_3^-, mg kg^{-1})	0.08	*<0.001*	0.51

p values less than 0.05 were considered to be significant.

Table 4. – Coefficients, significance (p) and R^2 values for multiple regression. Water-filled pore space (WFPS) and soil mineral N (N_m) when combined are significant parameters to predict N_2O emission

Soil parameter	Multiple regression		
	Value	*p*	R^2 value
Water Filled Pore Space (%)	0.06	*<0.001*	0.60
Soil Mineral N (NH_4^+ & NO_3^-, mg kg^{-1})	0.08	*<0.001*	0.60

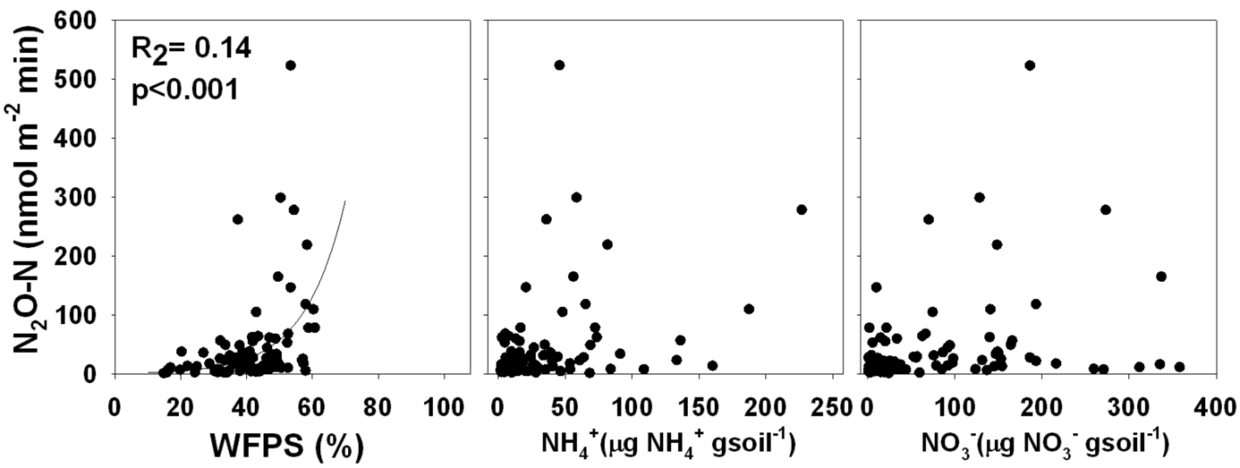

Figure 5. Relationship between water-filled pore space and concentration of NO_3^- and NH_4^+ in the soil and N_2O emissions from Nickels soil lab almond orchard. Data was collected during all the experimental season, from Fall 2009 to Winter 2010.

Fluxes of ^{15}N into roots, aboveground biomass and nitrous oxide

Root uptake from treatment one ($^{15}NO_3^-$) showed differences by depth over a sampling period of 36 hours after $NH_4{}^{15}NO_3$ injection (**Table 1**). The greatest enrichment was found in the 0-10 and 11-20 cm depths. Enrichment decreased by depth to 41-50 cm. These results suggested rapid root nitrogen uptake in the upper soil profile.

The roots are the primary route for nitrogen uptake and movement into the almond fruit. Furthermore, roots are in direct competition with microbes that may use this fertilizer for the undesirable production of N_2O gas. Results from root uptake of $^{15}NH_4^+$ are to come.

Two trees were set up with two sprinklers and the other 2 trees were set up with one sprinkler .The first fertilizer $^{15}NH_4NO_3$ was applied through one sprinkler to one tree and twice as much of the same fertilizer was applied to the second tree with the use of 2 sprinklers. The second fertilizer $NH_4{}^{15}NO_3$ was applied the same way to tree 3 and 4 allowing for the enrichment of four almond trees in total.

For both the full and half rates the $^{15}NH_4^+$ treatment showed higher enrichment in ^{15}N as compared to the $^{15}NO_3^-$ treatment (**Table 2**). This result was consistent for both the hull + shell and kernel fractions of the almond fruit. Uptake and translocation of nitrogen in the ammonium form may follow a more direct pathway to the almond fruit.

Fluxes of $^{15}N_2O$ in the $^{15}NO_3^-$ were substantially lower than the $^{15}NH_4^+$ treatment (**Figure 6**). Since N_2O is the product of two potential pathways, this result suggests nitrification may play a greater role. This observation is consistent with higher fluxes in UAN as compared to CAN (Schellenberg et al. 2010). Future work will identify the proportion of N_2O from nitrification as compared to denitrification (Panek et al. 2000, Baggs 2008).

Table 5. ^{15}N enrichment of almond roots (< 1.0 mm) at multiple soil depths following fertigation with a $^{15}NO_3^-$ labeled fertilizer consisting of NH_4NO_3 . Shown are root enrichments observed at 36 h following isotope application

Treatment	Depth (cm)	^{15}N (atom-%)
$NH_4{}^{15}NO_3$ (10 atom %)	0-10	0.455
$NH_4{}^{15}NO_3$	11-20	0.455
$NH_4{}^{15}NO_3$	21-30	0.423
$NH_4{}^{15}NO_3$	31-40	0.374
$NH_4{}^{15}NO_3$	41-50	0.370

Table 6. 15-Nitrogen enrichment of ammonium ($^{15}NH_4^+$) and nitrate ($^{5}NO_3^-$) treatments at full or half enrichment rates of almond fruit at harvest split into hull+shell and kernel

		^{15}N (atom-%)	
Treatment	Rate	Hull + Shell	Kernel
$^{15}NH_4NO_3$	Full	0.436	0.443
$^{15}NH_4NO_3$	Half	0.414	0.421
$NH_4{}^{15}NO_3^-$	Full	0.381	0.387
$NH_4{}^{15}NO_3^-$	Half	0.374	0.376

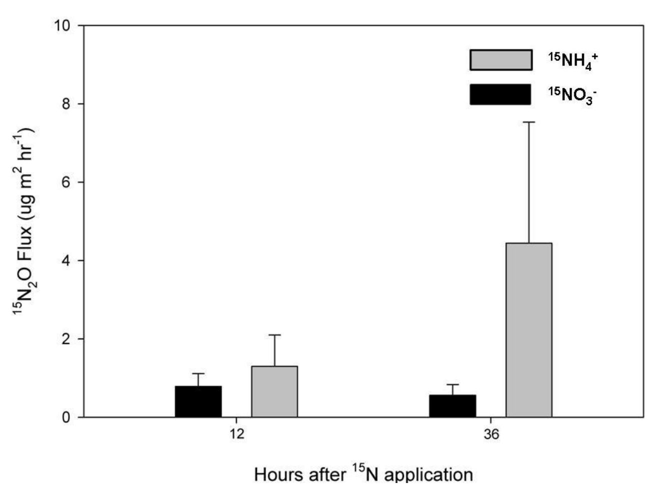

Figure 6. Representative diagram at the tree scale of nitrogen cycling from agronomic uptake and crop export in addition to soil nitrogen inputs and nitrous oxide emissions

Methane Oxidation by Orchard Soils

A further finding of our investigations (**Table 6, Figure 7**) was the discovery of instances where methane (CH_4) was oxidized by methanotrophic bacteria of almond orchard soils. The observation was made in an orchard on a sandy loam soil with a low carbon content of 0.3%. This quantity of C is extremely low, though not atypical for many California soils particularly in the Southern San Joaquin Valley, where most agricultural soils are reported to have less than 1% C content. Nonetheless, at the Nickel's Soil Laboratory experiment where soil carbon content was somewhat higher at 1.25 to 1.65% C, soils acted as net sources for CH_4 emissions (**Table 6**).

Table 6: Seasonal CH_4 emissions (lbs $acre^{-1}$), irrigation amounts and CO_2-equivalents for two different fertilizers, urea ammonium nitrate (UAN) and calcium ammonium nitrate (CAN), and three methods of N delivery (conventional surface drip, microjet sprinkler and subterranean drip). Shown are data from 2 to 3 seasons with fertilizer applications of from 210 to 235 units of N $acre^{-1}$. The data indicated that some, limited oxidation of CH_4 can occur in these soils.

Crop	Soil Texture	Management	N-Applied (lbs $acre^{-1}$ $year^{-1}$)	Irrigation (in ha^{-1})	CH_4 (lbs $acre^{-1}$ $year^{-1}$)	CO_2-equivalent (lbs $acre^{-1}$ $year^{-1}$)
Almond	Sandy Loam	CAN	200	52	-0.07 ± 0.01	-1.8 ± 0.3
Almond	Sandy Loam	UAN	200	52	-0.05 ± 0.02	-1.3 ± 0.5
Almond	Sandy Clay Loam	Surface Drip	210	–	0.05 ± 0.13	1.3 ± 3.3
Almond	Sandy Clay Loam	Microjet	210	–	0.14 ± 0.13	3.5 ± 3.3
Almond	Sandy Clay Loam	Sub Drip	210	–	-	–

For the almond orchards we examined, CH_4 oxidation occurred not infrequently, but no discernable pattern emerged and occasional positive daily emissions were also observed. Average daily CH_4 emissions from the uncultivated alleyway were consistently positive albeit small at less than 0.1 g CH_4-C ha^{-1} day^{-1}. When taken over the entire growing season, orchards we examined on well drained sandy-loam soils with low carbon content were net sinks for atmospheric CH_4 while those from a poorly drained, more compacted sandy-clay-loam soil with higher C content were sources (**Table 6**). Nonetheless, we have observed up to 2 lbs CH_4 oxidized per hectare per year (48 CO_2 equivalent lbs) in high clay and C vineyard soils with lower irrigation amounts.

We have noted that the amount of CH_4 oxidation was greater from the lower nitrogen fertilizer regimens. For UAN 25.3, 49.5 and 41.7 g CH_4-C ha^{-1} were oxidized in spring 2009, spring 2010 and summer 2010, respectively, while the quantities oxidized during post-harvest N applications in 2009 and 2010 and during the winter applications during 2010 were 81.0, 59.3 and 68.9 g CH_4-C. The results were similar with CAN; in spring 2009 and 2010 and summer 2009 the g CH_4-C ha^{-1} oxidized were 23.3, 44.1, and 29.6 while the values in post-harvest 2009 and 2010 and winter 2010 were 71.3, 74.7 and 62.2 g CH_4-C ha^{-1} (**Table 7**). In summer 2009 and 2010 the amount of CH_4-C oxidized was the highest in the higher fertilizer regime for UAN (64.2 g CH_4-C ha^{-1}) and CAN (68.5 g CH_4-C ha^{-1}). These results suggest CH_4 oxidation is inhibited by higher levels of N fertilizer in the system.

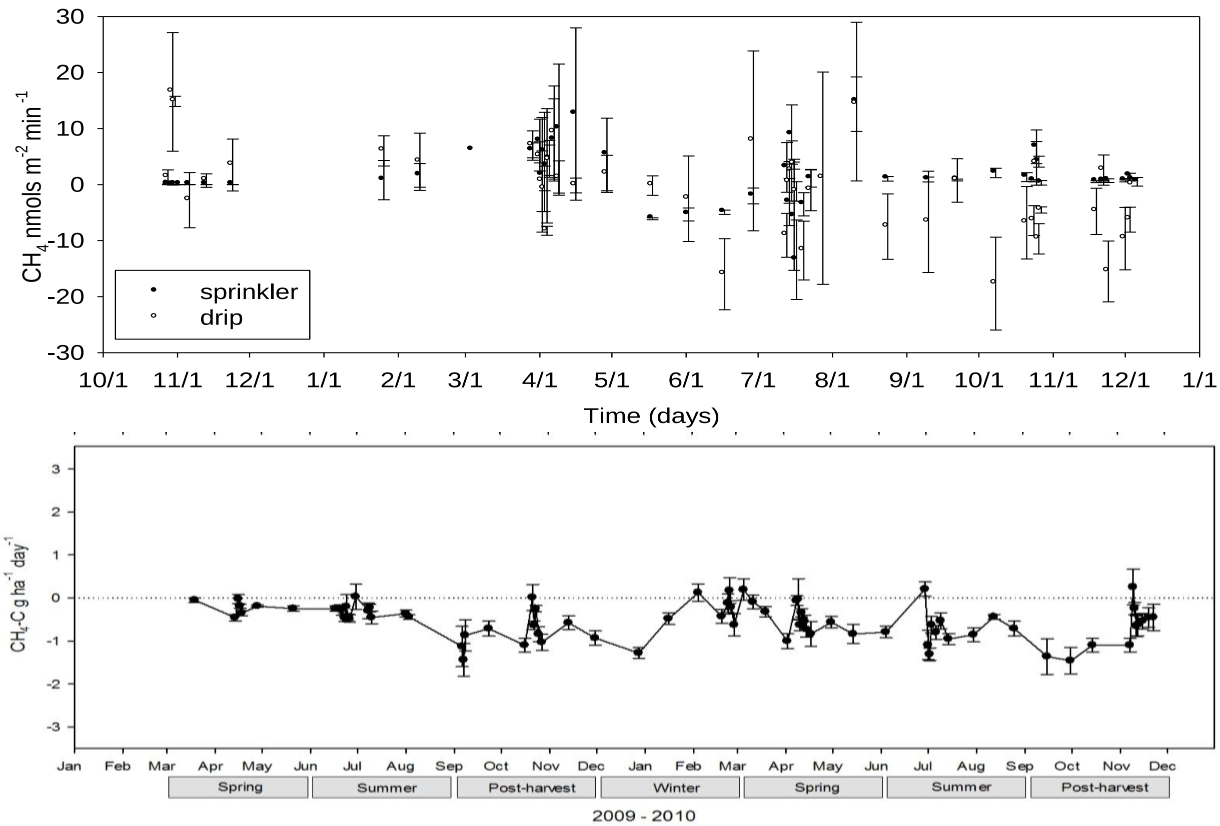

Figure 7. CH_4 flux (nmols m^{-2} min^{-1}) for sprinkler (filled symbols) and drip (open symbols) irrigation in an almond orchard on a sandy clay loam soil. This value includes the total CH_4 mass emitted from the wet area calculated as the integral by sectors of the emission or absorption from the wetted area around the emitter plus the dry area emission calculated considering a constant CH_4 flux value.

Table 7. Cumulative CH_4 oxidation (g CH_4-C ha^{-1}) during seasonal periods in 2009-2010

	CH_4 oxidation (g CH_4-C ha^{-1})			
	Winter	Spring	Summer	Post-harvest
		2009		
CAN	-	23.3 ± 7.06	29.6 ± 12.2	71.3 ± 34.6
UAN	-	25.3 ± 5.32	64.2 ± 9.80	81.0 ± 18.6
		2010		
CAN	62.2 ± 9.61	44.1 ± 9.20	68.5 ± 18.7	74.7 ± 16.9
UAN	68.9 ± 20.1	49.5 ± 12.4	41.7 ± 20.5	59.3 ± 32.1

These results have indicated there is a moderate offset opportunity for GHG production by the system if we can learn to take advantage of conditions that foster CH_4 oxidation. Soil water content, temperature and the concentration of ammonia, nitrate and N_2O are factors known to affect the rate of methane oxidation in soil (Hanson & Hanson, 1996) and our results show how WFPS affects N_2O emissions. The use of microirrigation systems, as in almond orchards, allows the regulation of these factors in order to minimize N_2O emissions and maximize CH_4 oxidation. Knowing the potential of the almond orchard soils to uptake CH_4 from the atmosphere, it is important to keep studying the orchard soil management that best enhances this process.

Research Effort Recent Publications:

Smart, DR, M Mar Alsina, MW Wolff, MG Matiasek, DS Schellenberg, JP Edstrom, PH Brown and KM Scow (2011) N_2O emissions and water management in California perennial crops. *In* G. Luo (Ed.) Agricultural Greenhouse Gas Emissions, American Chemical Society, Baltimore MD USA. (in press)

Suddick, EM, GM Garland, KL Steenwerth, **DR Smart** and JW Six (2011) Discerning agricultural management effects on nitrous oxide emissions from conventional and alternative cropping systems: A California case study. *In* G. Luo (Ed.) Agricultural Greenhouse Gas Emissions, American Chemical Society, Baltimore MD USA. (in press)

Suddick E, KM Scow, WR Horwath, LE Jackson, **DR Smart**, JP Mitchell and J Six (2010) The potential for California agricultural crop soils to reduce greenhouse gas emissions: A holistic approach. *Advances in Agronomy* 107:123-162.

Smart, DR, CM Stockert M Matiasek and RB Boulton (2010) Spatial constraints on N_2O emissions and microbial activity during drip irrigation of perennial crops. *Ecological Applications* (in revision)

References:

Abbasi, M.K., and W.A. Adams. 2000. Gaseous N emission during simultaneous nitrification-denitrification associated with mineral N fertilization to a grassland soil under field conditions. *Soil Biology & Biochemistry*, 32:1251-125

Allen, D.E., G. Kingston, H. Rennenberg, R.C. Dalal, S. Schmidt (2010) Effect of nitrogen fertilizer management and waterlogging on nitrous oxide emission from subtropical sugarcane soils. *Agriculture, Ecosystems and Environment*, 136:209-217.

Baggs, E. M. (2008) A review of stable isotope techniques for N2O source partitioning in soils: recent progress, remainng challenges and future considerations. *Rapid Communications in Mass Spectrometry*, 22:1664-1672.

Beare, M.H., E.G. Gregorich, and P. St-Georges (2009) Compaction effects on CO_2 and N_2O production during dry and rewetting of soil. *Soil Biology & Biochemistry*, 41:611-621.

Bloom, A.J., D.R. Smart, P. Searles and D. Nguyen (2002) Elevated carbon dioxide concentrations inhibit nitrate assimilation in wheat shoots. *Proceedings of the National Academy of Sciences of the United States of America,* 99:1730-1735.

Bouman, A.F., L.J.M. Boumans and N.H. Batjes (2002) Emissions of N_2O and NO from fertilized fields: Summary of available measurement data.*Global Biogeochemical Cycles*, 16, 1-13.

Brooks, P. D., and J. M. Stark. 1989. Diffusion Method To Prepare Soil Extracts for Automated Nitrogen-15 Analysis. *Soil Science Society of America Journal*, 53:1707-1711.

Carlisle E, KL Steenwerth and DR Smart (2006) Conversion of oak woodlands to vineyards alters physical constraints on soil CO_2 respiration in Mediterranean climate ecosystems. *Journal of Environmental Quality,* 35:1396-1404.

Davidson, E.A., P.A. Matson, and P.D. Brooks (1996) Nitrous Oxide Emissio Controls and Inorganic Nitrogen Dynamics in Fertilized Tropical Agricultural Soils. *Soil Science Society of American Journal*, 60:1145-1152.

Hanson, R.S. and T.E. Hanson (1996) Methanotrophic bacteria. *Microbiological Reviews*, 60:439-471.

Khalil, K., B. Mary, and P. Renault (2004) Nitrous oxide production by nitrification and denitrification in soil aggregates as affected by O_2 concentration. *Soil Biology & Biochemistry*, 36:687-699.

Liu C., Zheng X., Zhou Z., Han S., Wang Y., Wang K., Liang W., Li M., Chen D., Yang Z. (2010) Nitrous oxide and nitric oxide emissions from an irrigated cotton field in Northern China. *Plant and Soil*, 332:123-134.

Lopus, S.E., M.P. Santibanez, R.H. Beede, R.A. Duncan, J. Edstrom, F.J.A. Niederholzer, C.J. Trexler, and P.H. Brown (2010) Survery examines the adoption of perceived best management practices for almond nutrition. *California Agriculture*, 64:149-154

Panek, J. A., P. A. Matson, L. Ortiz-Monasterio, and P. Brooks (2000) Distinguishing nitrification and denitrification sources of N2O in a Mexican wheat system using 15N. *Ecological Applications*, 10:506-514.

Sauer T.J., S.R. Compston, C.P. West, G.Hernandez-Ramirez, E.E. Gbur, T.B. Parkin (2009) Nitrous oxide emissions from a bermudagrass pasture: Interseeded winter rye and poultry litter. *Soil Biology and Biochemistry*, 41:1417-1424.

Schellenberg, D. L., M. Alsina, C. Stockert, and D. Smart (2010) Seasonal Variability of Nitrous Oxide Emissions from Two Fertilizers in a California Almond Orchard. *ASA-CSSA-SSSA International Annual Meetings*, Long Beach, CA.

Schellenberg, D. L., M. Alsina, S. Muhammad, J. Jenkins, C. Almanza, C. Stockert, B. Sanden, P. Brown, and D. Smart (2011) Nitrous Oxide and Productivity Index for California Almond. *ASA-CSSA-SSSA Internatinal Annual Meetings*, San Antonio, TX.

Smart, D.R. and A.J. Bloom (2001) Leaves emit nitrous oxide during nitrate assimilation. *Proceedings of the National Academy of Sciences of the United States of America,* 98:7875-7878.

Smart, D.R. and J. Peñuelas (2005) Changes in soil CO_2 respiration following precipitation onto dry soils: An investigation of elevated CO_2 using Mediterranean plants. *Applied Soil Ecology*, 28:247-257.

Smart, D.R., J.M. Stark and V. Diego (1999) Resource limitations to nitric oxide emissions from a sagebrush-steppe ecosystem. *Biogeochemistry*, 47:63-86.

Smart, D.R., C.M. Stockert, M. Matiasek and R.B. Boulton (2010) Spatial constraints on N_2O emissions and microbial activity during drip irrigation of perennial crops. *Ecological Applications* (in revision)

Smart, DR, M Mar Alsina, MW Wolff, MG Matiasek, DL Schellenberg, JP Edstrom, PH Brown and KM Scow (2011) N_2O emissions and water management in California perennial crops. *In* G. Luo (Ed.) Agricultural Greenhouse Gas Emissions, *American Chemical Society*, Baltimore MD USA.

Stark, J.M., D.R. Smart**,** K. Haubensak and S.C. Hart (2002) Regulation of nitric oxide emissions from forest and rangeland soils of Western North America. *Ecology*, 83:2278-2292.

Steenwerth, K.L., D.L. Pierce, R.G. Spencer, E.A. Carlisle and D.R. Smart. (2009) Disturbance and precipitation effects on soil respiration under Mediterranean conditions. *Soil Science Society of America Journal*, 74:231-239.

Suddick, E.M., K.M. Scow, W.R. Horwath, L.E. Jackson, D.R. Smart, J.P. Mitchell and J.W. Six (2010) The potential for California agricultural crop soils to reduce greenhouse gas emissions: A holistic approach. *Advances in Agronomy*, 107:123-162.

Suddick, E.M., G.M. Garland, K.L. Steenwerth, D.R. Smart and J.W. Six (2011) Discerning agricultural management effects on nitrous oxide emissions from conventional and alternative cropping systems: A California case study. *In* G. Luo (Ed.) Agricultural Greenhouse Gas Emissions, American Chemical Society, Baltimore MD USA. (in press)

Venterea, R.T., M.S. Dolan, and T.E. Ochsner (2010) Urea decreases nitrous oxide emissions compared with anhydrous ammonia in a Minnesota corn cropping system. Soil Science Society of American Journal 74:407-418

Verma, A., L. Tyagi, S. Yadav, and S.N. Singh (2006) Temporal changes in N_2O efflux from cropped and fallow agricultural fields. *Agriculture, Ecosystems and Environment*, 116:209-215.

Volder, A., L.J. Anderson, D.R. Smart, A.J. Bloom, A.N. Lakso and D.M. Eissenstat (2009) Estimating nitrogen uptake of individual roots in container and field-grown plants using a ^{15}N-depletion approach. *Functional Plant Biology*, 36:1-8.