Greenhouse Gas Emissions from Almond Orchard Floors and Measuring Nitrogen Mobilization Using an Isotopic Approach

Project No.: **11-AIR2-Smart**

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Objectives:

Nitrogen (N) 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 (AB32), and the US EPA's recent endangerment finding for greenhouse gases (GHGs) such as CO_2, N_2O and CH_4 (http://www.epa.gov/climatechange/) that 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 nitrogen. The project integrates with 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 application of fertilizer (system and fertilizer source) 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 N (NH_4^+, NO_3^-, NH_3, and N_2O) 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 the Intergovermental Panel on Climate Change (IPCC) assessment values adopted by most regulatory organizations.

1) We've found that cumulative N_2O emissions from CAN are substantially less than from UAN, and peak N_2O emissions from CAN are significantly less during summer conditions compared to UAN (Schellenberg et al. 2012).
2) We've found that N_2O emissions were significantly diminished when microjet sprinklers were utilized as the fertigation delivery system (Alsina et al. *In press*).
3) We have discovered two cases where methane was apparently being absorbed (oxidized) by methanotrophic microorganisms in orhard soils. With a climatic warming potential 25 times greater that CO_2 this helps offset GHG production and offers a possible mitigation potential to be investigated (Schellenberg et al. 2012, Alsina et al. *In press*).
4) We have demonstrated the ability to estimate N transformations (mineralization, nitrification and immobilization) and to trace ^{15}N into root and soil pools from NH_4^+ and NO_3^- fertilizer sources with detected crop recovery within 60 days.

Interpretive Summary:

In addition to acquiring baseline rates of nitrous oxide emissions (N_2O) for fertilization rates of approximately 200 to 235 units N acre^{-1}, we have identified at least two best management practice (BMP) approaches to N fertigation. In most cases we have documented that N_2O emissions per unit of N fertilizer applied to California almonds are substantially less than the amount estimated by emission factors (EFs) utilized for greenhouse gas emissions assessments (IPCC, 2007). Furthermore, our efforts using isotopic tracers have led to preliminary estimates of N transformations (mineralization, nitrification and immobilization), as well as evidence for soil and fine root sinks for N in less than 12 hours and nut crop recovery within 60 days.

Our preliminary results have indicated that N_2O emissions are diminished for calcium ammonium nitrate (CAN) as the N-source as compared with urea ammonium nitrate (UAN) when the method of delivery is microjet sprinkler irrigation. During summer, peak

N_2O emissions from applications of UAN fertilizer were significantly greater than emissions from CAN application ($p < 0.0001$) (Schellenberg et al. 2012). 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. Our investigation of CAN versus UAN was evaluated over an entire growing season. Nitrous oxide emissions after fertilizer applications followed distinct patterns according to season (soil and ambient temperature and soil moisture conditions). 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 soils exceed 50% water-filled pore space (WFPS), and points to the real possibility of modifying water (and N) application to diminish N_2O emissions. We have carried out this experiment in conjunction with intensive monitoring of yields in cooperation the Brown Lab. We integrated with other research UC researchers and modified an index for yield-scaled estimates of global warming potential (GWP) to fit almond.

In another unexpected development, we found that N_2O emissions were diminished under microjet spray fertigation than for conventional drip irrigation, and we have verified this result by monitoring emissions patterns over the course of a season and quantifying the amount of N_2O both spatially and temporally (Alsina et al. *In press*). We have been successful in capturing the complex spatial distribution of N and water, and therefore N_2O emissions during fertigation. Microjet sprinklers apply N and water to a more extensive area of the orchard floor, but our findings indicated the surface soil where most microbial denitrification activity occurs dries more rapidly than the zone of drip applied water (and N). We have found most variation in N_2O emission is explained by the percentage of water-filled pore space greater than approximately 50% ($R^2 = 0.40$. We continue to directly communicate these results to the California Air Resources Board (CARB).

Materials and Methods:

Seasonal N_2O Emissions

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 (Smart et al. 1999, Smart and Bloom 2001, Bloom et al. 2002, Smart and J 2005, Carlisle et al. 2006, Steenwerth et al. 2009, Volder et al. 2009, Suddick et al. 2010, Smart et al. 2011, Suddick et al. 2011, Schellenberg et al. 2012). 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 gas species 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 its absorption and assimilation of N by trees.
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 thought to correspond to periods of highest nitrogen demand and when fertilizer N is applied in a targeted manner. Furthermore, we targeted these measurements for periods when soil and ambient temperatures and soil moisture that 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 noting that the periods of highest N-demand are spring and summer. The above mentioned seasonal (and phenological) periods occurred during the following general dates: Winter, Nov. 1-Jan. 31; Spring, Feb. 1-April 30; Summer, May 1-July 31 and Fall, Aug. 1-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 (sandy-clay) loam soil and at the Nickels Soil Laboratory (sandy loam) in Arbuckle California. The timing of all cultural practices are carried out in close conversation with University of California Cooperative Extension, Bakersfield, under the guidance of Blake Sanden including, primarily, water and nitrogen applications.

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

After fertilizer application with irrigation water, plots were allowed to dry for up to 9 day. The wetting, drying and rewetting phases of California irrigated almond orchards present a valuable opportunity to add to similar observations under field and laboratory conditions and under seasons where rates of drying differed (Beare et al. 2009, Allen et al. 2010).

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 (microjet spray versus conventional drip). To achieve this objective, N_2O emissions were monitored after fertigation events and over an entire season using a series of transects in a microsprinkler and in a drip irrigated almond orchard (**Figure 1**).

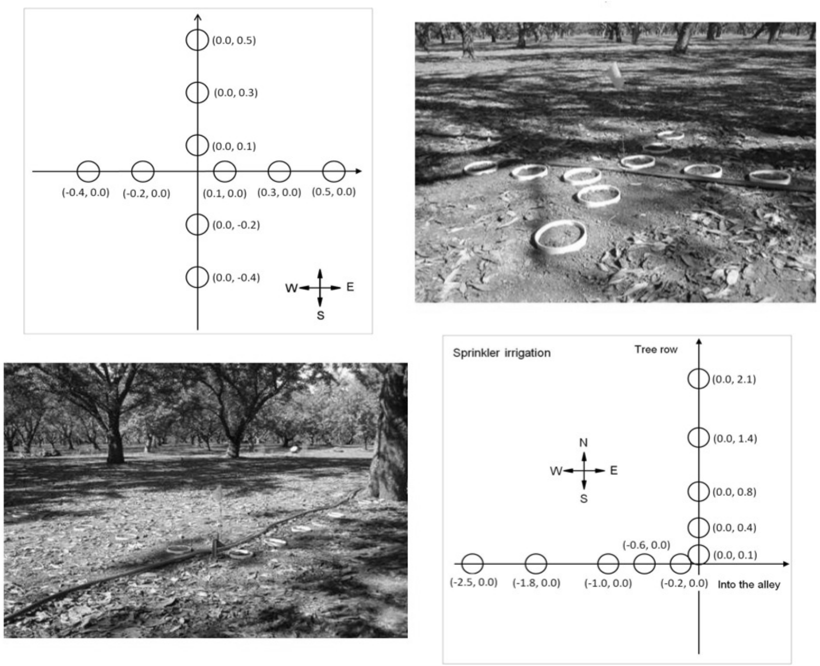

Figure 1. Collar distribution (scheme and picture) for sprinkler irrigation and for drip irrigation. Pictures correspond to the collars installed in Nickels soil lab Almond Orchard in Arbuckle, CA.

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 + UAN. These models provide the basis for scaling emissions to the orchard level using geometric exercises that divide the orchard into areas with extremely low emissions (eg. driveways) and areas with relatively high emissions (the fertigation wet-up zone).

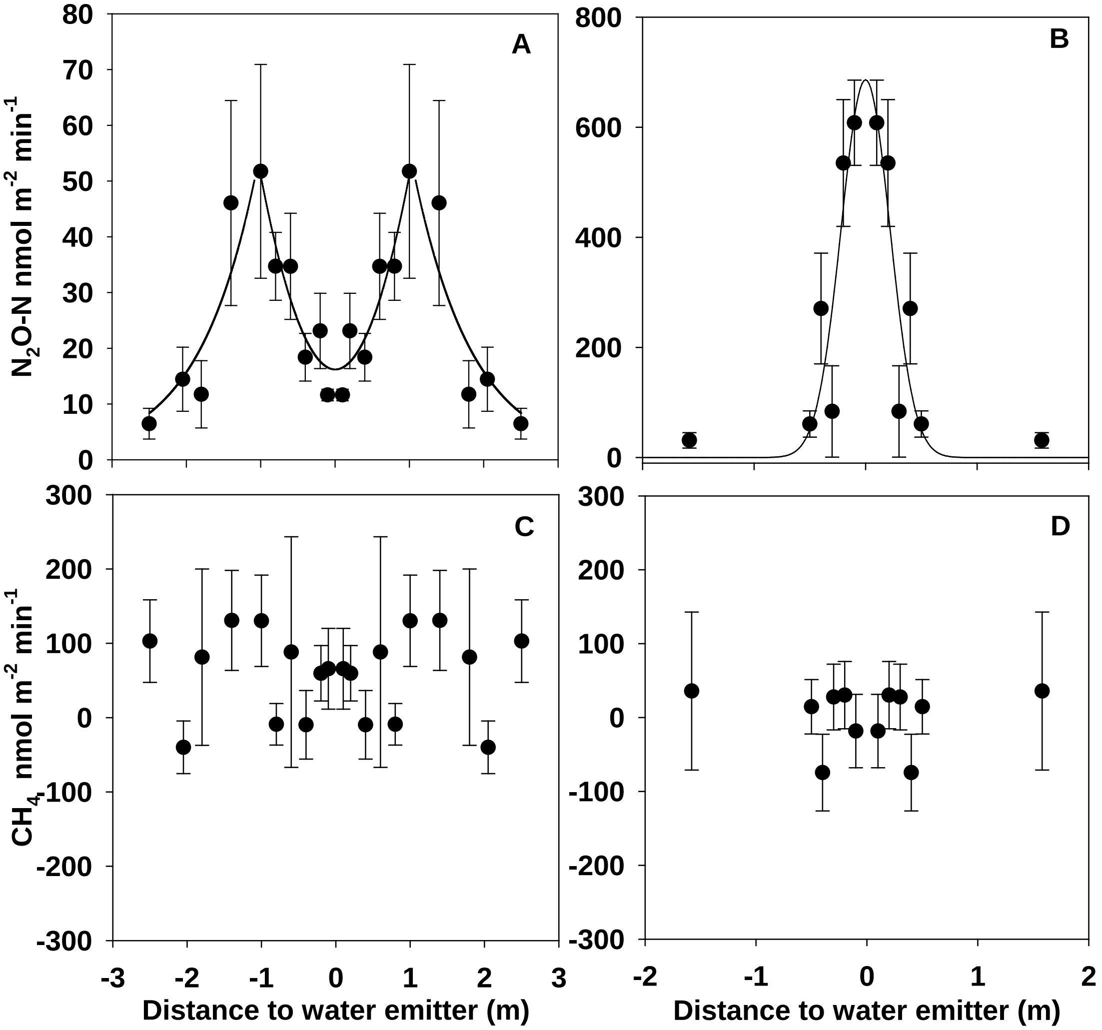

Figure 2: Distribution of instantaneous N_2O emissions and net CH_4 fluxes for microsprinkler irrigation "sprinkler" (panels A and C) and drip irrigation (panels B and D). A two step function was fitted to the N_2O emission scatter for microsprinkler irrigation: the first function was a parabola in the area between the center (emitter position) and the maximum measured emission at about 1 m from the emitter: the second function was an exponential decay from the maximum emission position to the edge of the wetted area. For the N_2O emissions in drip irrigation, the best fit was a 2 parameter Gaussian (Smart et al. 2011). Net CH_4 fluxes did not show any consistent discernible pattern in the wet-up areas.

Nitrogen mobilization using an isotopic tracer approach

The effective management of nitrogen (N) fertilizers is one of the most urgent issues confronting the agricultural community. On the arid lands in California, almond growers use advanced fertilization practices including micro-irrigation systems that deliver N in solution with water (fertigation) targeted to meet peak tree demand. In summer 2010, we examined gross N transformation rates and N assimilation by microbes and tree roots over two days after fertilization (DAF) using a combined isotope dilution and tracer approach. We deployed a transect of closed chambers to spatially constrain $^{15}N_2O$ flux during the experimental period and sampled soil to 50 cm at 10 cm intervals to extrapolate measurements to the tree scale.

Four trees were identified for targeted ^{15}N enrichment during the summer 2010. Treatments of $^{15}NH_4NO_3$ and $NH_4{}^{15}NO_3$ (10% ^{15}N a.e.) were pulse-injected overnight through the micro-jet sprinkler irrigation system. Gas sampling was conducted at 12, 36 and 72 hours after ^{15}N injection. Soil sampling was conducted in duplicate to 0-10, 11-20, 21-30, 31-40 and 41-50 cm at 0, 12 and 36 hours. Soil was oven-dried and roots were dry-sieved into fractions separated by diameter. Separate aliquots of soil were immediately frozen in sterile bags and stored at -80^{o}C. Soil KCl extracts were diffused into $^{15}NH_4^+$ and $^{15}NO_3^-$ fractions (Brooks and Stark 1989). Almond roots and fruits were ground to pass through a 2mm sieve and packed into tin capsules. Samples for isotopic analysis were sent to the UC Davis Stable Isotope Facility.

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 per 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 situations 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 dripper. 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 5**). In contrast to drip, sprinkler distribution showed the peak of emission at a distance around 1m from the center and then it decreased exponentially until values close to zero were reached at distances of 2.5 – 3 m from the emitter (**Figure 2**).

Progress on Developing Comprehensive N_2O Emissions and Carbon Footprints

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). Multiple microbial processes contribute to the production of N_2O. Past work demonstrated the equviliant contribution of nitrification and denitrification to the total N_2O emissions following a fertilization event for wheat (Panek et al. 2000). Few measurements exist for microirrigated crops in the arid West of North America. Our work demonstrates a growing understanding of seasonal variability during event related emissions for microirrigation systems. In this case, the 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}), California emissions factors (EF_{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). Shown are data from 2 to 3 seasons with fertilizer applications of 200 to 210 units of N acre^{-1}. Statistical significance ($p \leq 0.05$) indicated that microjet systems had significantly lower emissions overall while CAN had significantly lower emissions periodically.

Crop	Location	Management	Units N (lbs ac^{-1})	EF_{Calif}	N_2O-N (lbs acre^{-1} yr^{-1})	CO_2-eq
Almond	Belridge	CAN	200	0.23%	0.9 ± 0.2	253
Almond	Belridge	UAN	200	0.35%	1.5 ± 0.4	444
Almond	Nickels	Surface Drip	210	0.68%	1.5 ± 0.2	427
Almond	Nickels	Microjet	210	0.25%	0.5 ± 0.1	158
Almond	Nickels	Sub Drip	210	–	–	–

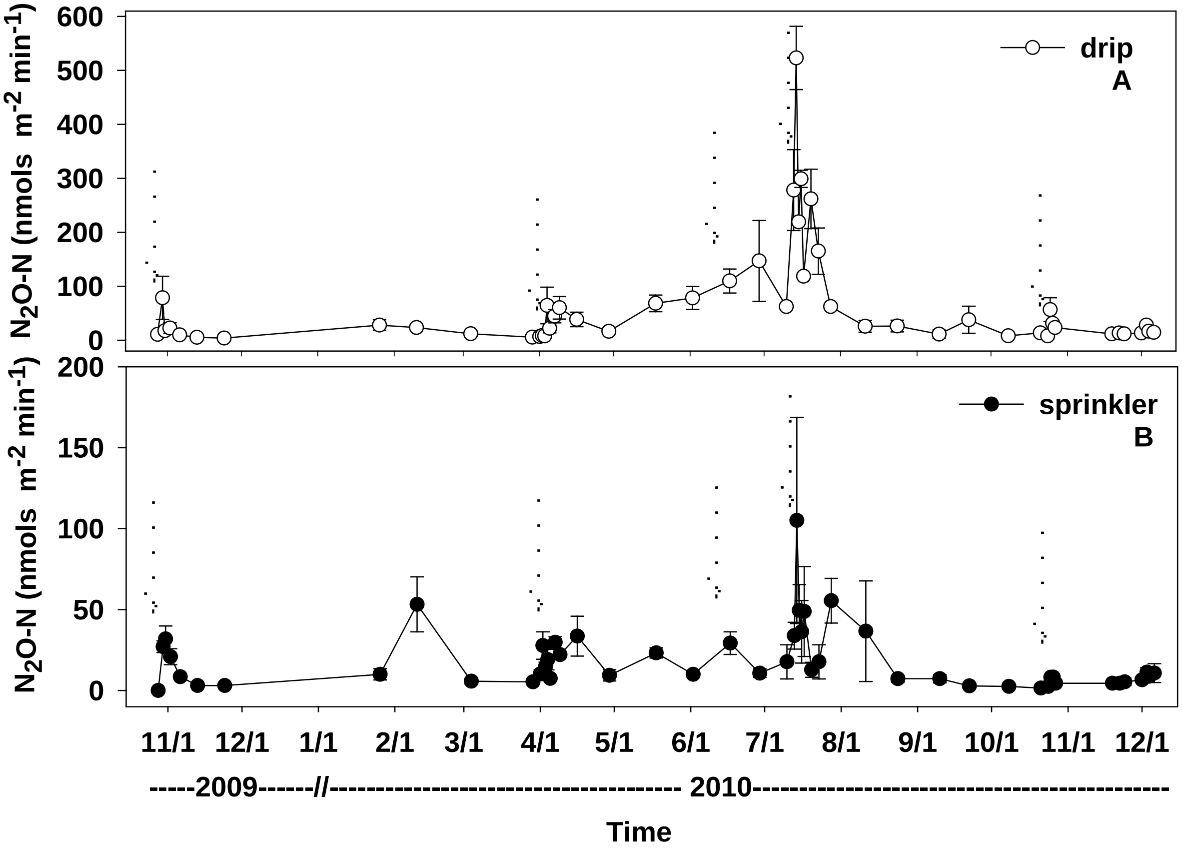

Figure 3. N_2O emissions (nmol N_2O-N m^{-2} min^{-1}) spatially scaled to the orchard level (fertigation and driveway areas) for microsprinkler irrigation “sprinkler” (filled symbols) and drip irrigation (open symbols). Total moles of N_2O emitted was estimated as the integral of the surface defined by the N_2O flux distribution around the fertigation emitters and scaled up using the number of emitters per hectare, plus the N_2O flux observed outside the wet-up area in the orchard driveways. Arrows represent dates when fertigation occurred.

For water distribution systems (drip versus microjet sprinkler, **Figure 3**) water distribution patterns are known by manufacturers and follow similar patterns so to some extent N_2O emissions may be spatially related to soil water content. Our data have indicated a relation between soil water and N_2O emissions. Other parameters that drive emissions, like NH_4^+ and NO_3^- substrates, were less important in influencing these emissions (**Figure 5**). From the defined distribution in each of the irrigation system, we calculated the total amount of N_2O emitted per unit of soil surface and time, and extrapolated it to a larger scale. We obtained the total amount in mass of N from N_2O emitted per hectare during the hours when N_2O emission peaked following fertigation. We monitored N_2O as described during one month (or until emission decreased to baseline values measured before the fertigation) after four fertigation events from fall 2009 to fall 2010. The maximum instantaneous rates in fall 2009 and 2010 (CAN, UREA 30 lbs acre^{-1}) never reached values of 100 nmols m^{-2} min^{-1}. The maximum instantaneous rates of N_2O-N emission corresponded to levels of 80 nmol N m^{-2} min^{-1} and 30 nmols N m^{-2} min^{-1} for drip and sprinkler irrigations respectively in fall 2009, and 60 and 10 nmols N m^{-2} min^{-1} for drip irrigation and sprinkler irrigation respectively in fall 2010. During the summer period, values for N_2O-N emission from drip irrigated soil were always significantly higher than those observed in sprinkler irrigated soil, and reached a peak of 500 nmols m^{-2} min^{-1}, 5 times higher than in sprinkler (**Figure 3**). The instantaneous rates were scaled to the orchard level and indicated that drip emitted significantly more N_2O that microjet sprinkler delivery (**Table 2**).

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 at 154 nmols N m^{-2} min $^{-1}$ for UAN and at 100 nmols N m^{-2} min $^{-1}$ for CAN following an application of 40 lbs N acre^{-1} and were not statistically significantly different (NS). In late spring, following a fertigated N application of 60 lbs N acre^{-1}, N_2O emissions peaked after 25 hours at 260 nmols N m^{-2} min $^{-1}$ for UAN and 182 nmols N m^{-2} min $^{-1}$ for CAN (NS). During summer fertigation (60 lbs N acre^{-1}) N_2O emissions peaked after 10 hours at 467 nmols N m^{-2} min $^{-1}$ for UAN and 167 nmols m^{-2} min $^{-1}$ for CAN and showed a significant difference ($p<0.0001$). In fall, peak N_2O emissions appeared following 60 hours and decreased to 128 nmols N m^{-2} min $^{-1}$ for UAN and 86 nmols N m^{-2} min $^{-1}$ for CAN (**Figure 4**). Past work by scientists in different geographical locations observed seasonal variability of N_2O emissions in relation to fertilizer management practices (Verma et al. 2006, Venterea et al. 2010).

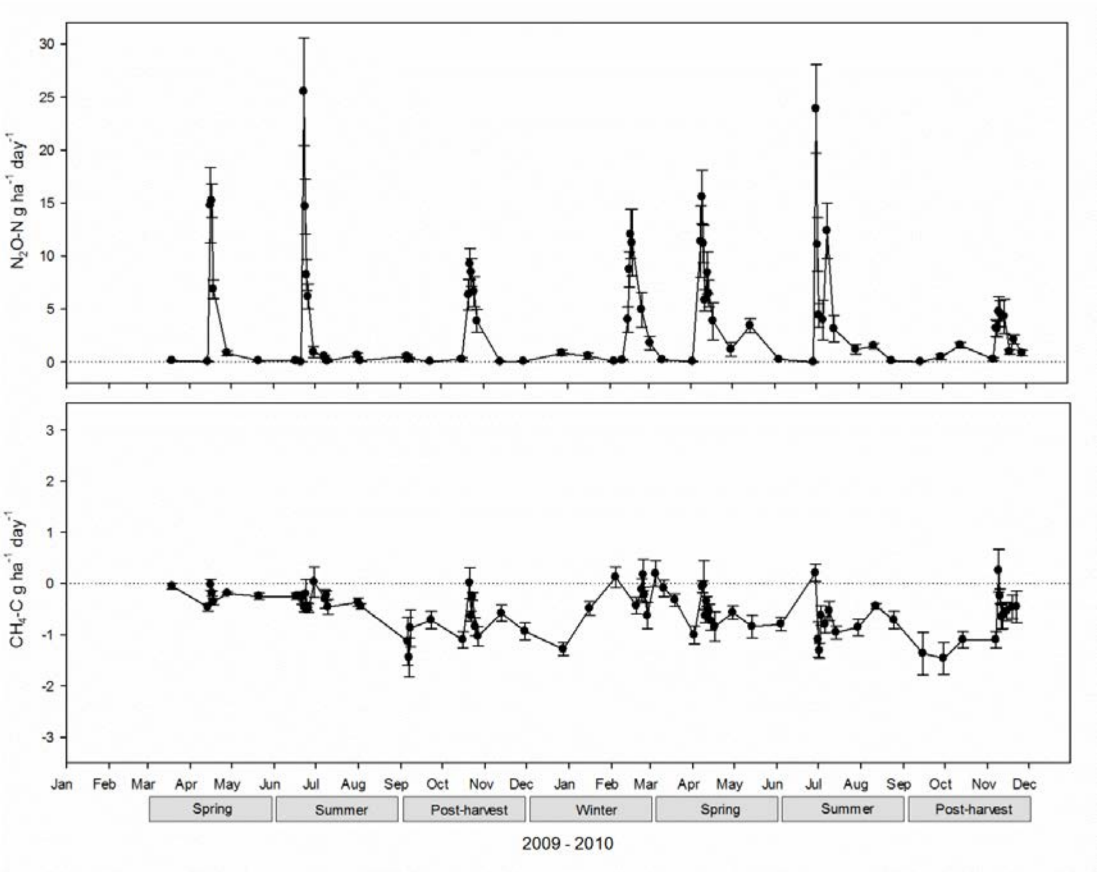

Figure 4. Seasonal patterns of N_2O emissions and CH_4 oxidation averaged across fertilizer treatments of urea ammonium nitrate (UAN) and calcium ammonium nitrate (CAN) during spring, summer, post-harvest and winter in 2009 and 2010**.** Data points represent mean values with standard error bars (n = 10) (Schellenberg et al. 2012).

Table 2. Integrated totals of N_2O-N emitted (kg/ha), net CH_4 flux (kg/ha), and amount of N applied (kg/ha) per event and per year, form of fertilizer used, either 17% N as calcium ammonium nitrate (CAN17) or 32% N as urea ammonium nitrate (UAN32), phenological stage at time of application, average soil temperature during event related N_2O emissions and statistical significance for five fertigation events that occurred during fall, spring and summer during 2009-2010. For the 2009-2010 season a total of 226 kg N/ha were applied while the post-harvest application in 2010 would correspond to the proximate season (see **Figure 4**). The N_2O emission and the net CH_4 flux represent the average of the spatial and temporal integrated values in each of the 3 sampled trees per irrigation treatment.

Season (stage)	**N Applied kg/ha (source)**	**Soil T (°C)**	**Days**		**Net Flux ($g\ ha^{1} event^{-1}$)** **micro-sprinkler**	**drip**	**P > F**
Fall (post-harvest)	33.6 (CAN17)	16.7 ± 0.4	*27	**N_2O-N** **CH_4**	23 ± 4 nd	63 ± 34 nd	[£]n.s. n.s.
Spring (post-bloom)	56.1 (CAN17)	13.1 ± 0.2	31	**N_2O-N** **CH_4**	80 ± 10 63 ± 90	121 ± 15 72 ± 52	$P < 0.05$ n.s.
Summer (maturing nut)	56.1 (UAN32)	19.6 ± 0.4	83	**N_2O-N** **CH_4**	242 ± 75 -47 ± 17	907 ± 145 -87 ± 94	$P < 0.05$ n.s.
Summer (hull-split)	56.1 (UAN32)	26.3 ± 0.3					
Fall (post-harvest)	33.6 (UAN32)	21.5 ± 0.3	29	**N_2O-N** **CH_4**	16 ± 2 11 ± 6	71 ± 16 -68 ± 28	$P < 0.05$ $P < 0.05$
						($kg\ ha^{-1}\ yr^{-1}$)	
					micro-sprinkler	**drip**	**P > F**
[+]Total Net GHG Flux				**N_2O-N** **CH_4**	0.60 ± 0.25 0.17 ± 0.45	1.61 ± 0.68 0.01 ± 0.17	$P < 0.05$ n.s.

* Number of days for which the event was monitored and emissions quantified.

[£] n.s. = not statistically significant at $P > 0.05$.

[+] Total emission including all the fertigation events and the periods between them.

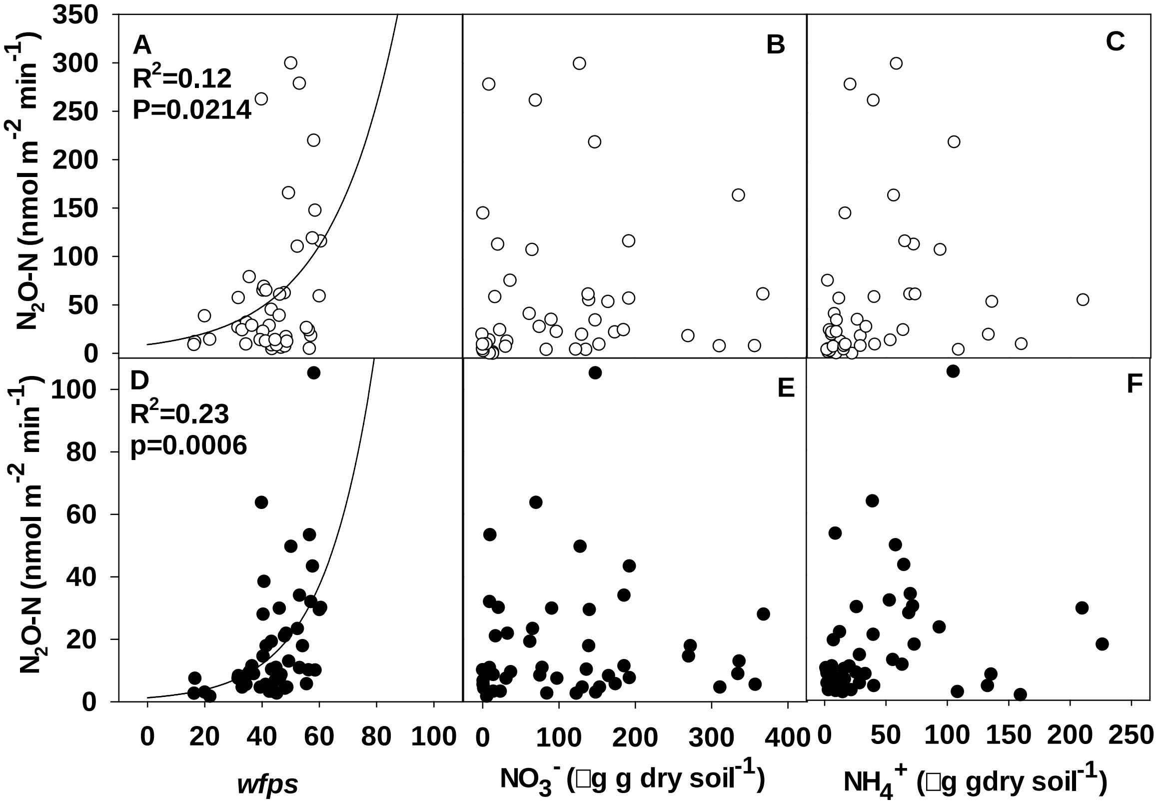

Figure 5. Relationship between N_2O emissions (nmol N_2O-N m^{-2} min^{-1}) and water-filled pore space (*wfps*, A and D), extractable soil NO_3^- (B and E) and soil NH_4^+ (C and F). Shown are the relationships for drip irrigation (open symbols, upper panels) and microsprinkler irrigation (closed symbols, lower panels). Data were collected throughout the experimental period from fall 2009 to winter 2010 at each time N_2O emissions were measured.

Table 3. Annual production cycle of fertilizer N inputs, N_2O emissions, percentage N_2O loss from N fertilizer input, CH_4 oxidation, global warming potential (GWP), almond kernel yield and yield-scaled GWP from seasonal periods of post-harvest 2009, winter 2009-2010, spring 2010, and summer 2010. Data represent mean values plus or minus standard error (n = 5).

	[a]CAN	UAN
Nitrous oxide emissions (kg N_2O-N ha^{-1} yr^{-1})	0.53 ± 0.11	0.80 ± 0.19
Total N fertilizer inputs (kg N ha^{-1} yr^{-1})	224	224
Percentage N_2O loss from N fertilizer input (%)	0.23 ± 0.05	0.35 ± 0.08
Nitrous oxide emissions (kg CO_2eq ha^{-1} yr^{-1})	248 ± 50.7	375 ± 88.6
Methane oxidation (kg CO_2eq ha^{-1} yr^{-1})	21.5 ± 5.11	21.0 ± 4.55
Global Warming Potential (kg CO_2eq ha^{-1} yr^{-1})	227 ± 54.5	354 ± 91.1
Total Almond Kernel Yield (Mg ha^{-1} yr^{-1})	3.81 ± 0.19	3.89 ± 0.17
Yield-scaled GWP (kg CO_2eq Mg^{-1})	60.9 ± 15.5	91.9 ± 24.6

[a] No significant differences were observed between fertilizer treatments ($p > 0.05$).

Yield Scaled Global Warming Potential

From this study, several key findings emerged that elucidate the GWP for this perennial system. First, the percentage of N_2O lost from the application of 224 kg N ha^{-1} was 0.23% from CAN and 0.35% from UAN (**Table 3**), and was substantially lower than found in a broad range of agricultural systems (Bouwman and Boumans 2002). The low N_2O emissions observed may be related to effective strategies for irrigation and fertilization that target water and N fertilizer with tree demand. A second finding of significance was frequent CH_4 oxidation across seasons and N fertilizer treatments. This sink resulted in an offset of N_2O emissions of 9.3% for CAN and 6.0% for UAN during the annual production cycle (**Table 3**). The global warming potential from N_2O emissions and CH_4 oxidation for CAN (248 kg CO_2eq ha^{-1} yr^{-1}) and UAN (375 kg CO_2eq ha^{-1} yr^{-1}) were on order of magnitude lower than an annual crop rotation in a similar climate (Scheer et al. 2008).

The use of micro-irrigation systems combined with split N fertilizer applications that coincide with tree demand fit previously described strategies to lower the GWP of agricultural systems (Freney 1997, Verma et al. 2006). In California, these strategies are scalable due to the adoption of micro-irrigation systems and the use of them to deliver soluble N fertilizers by a majority of almond growers (Lopus et al. 2010). Chemical tools such as urease or nitrification inhibitors could reduce the greater GWP observed in the UAN treatment (Bremner 1997, Halvorson et al. 2010). Furthermore, the opportunity to deliver soluble N fertilizer with higher frequency and lower concentrations may further reduce N_2O emissions and improve conditions for CH_4 oxidation because levels of soil mineral N would be less dynamic.

A recent agronomic assessment of major grain crops reported the average yield-scaled GWP from 22 studies of wheat (166 kg CO_2eq Mg^{-1}) and 19 studies of maize (185 kg CO_2eq Mg^{-1}) (Linquist et al. 2012). This comprehensive review provides a valuable metric for other agricultural systems where GWP in relation to crop yields is essential for the implementation of effective management strategies. The almond kernel yield in this study was not significantly different between fertilizer treatments (**Table 3**). As a result, the yield-scaled GWP from UAN (91.9 kg CO_2eq Mg^{-1}) was greater than CAN (60.9 kg CO_2eq Mg^{-1}) due to greater N_2O emissions generated during the annual production cycle. To date, this study reports the first account of yield-scaled GWP for a perennial crop.

At the fertilization rate followed in this study, almond kernel yield was 87% and 94% of maximum yield for CAN and UAN, respectively (Muhammad and Brown unpublished data). Under maximum yield conditions of 308 kg N ha^{-1}, we would expect yield-scaled GWP to be approximately 18% greater given the same percentage N_2O loss from N fertilizer input and proportion of N_2O emissions offset by CH_4 oxidation (**Table 3**). The lowest yield-scaled GWP for wheat (102 kg CO_2eq Mg^{-1}) and maize (140 kg CO_2eq Mg^{-1}) were achieved at 92% of maximum yield (Linquist et al. 2012). The 11 year old age of the orchard suggests higher future yields, while alterations to irrigation and fertilization strategies may further reduce N_2O emissions and stimulate CH_4 oxidation to optimize yield-scaled GWP.

Nitrogen mobilization using an isotopic tracer approach

Table 4. Gross N transformations (mineralization, nitrification, DNRA) and consumption rates, N sinks via soil (assimilation) and roots (uptake), and N_2O flux one (DAF 1) and two (DAF 2) days after fertilization with $^{15}NH_4{}^{14}NO_3$ and $^{14}NH_4{}^{15}NO_3$ at 120 lb N ac^{-1}.

	DAF 1	DAF 2
	g N tree^{-1} day^{-1}	
Gross mineralization (m)	15.5	37.1
NH_4 consumption (c_{NH4})	116	70.5
Gross nitrification (n)	171	67.9
NO_3 consumption (c_{NO3})	244	101
DNRA	16.2	24.0

	DAF 1	DAF 2
	g N tree^{-1} day^{-1}	
Soil assimilation from $^{15}NH_4{}^{14}NO_3$	80.9	33.6
Soil assimilation from $^{14}NH_4{}^{15}NO_3$	20.0	10.2
Root uptake from $^{15}NH_4{}^{14}NO_3$	1.16	1.67
Root uptake from $^{14}NH_4{}^{15}NO_3$	1.26	1.49

	DAF 1	DAF 2
	mg N tree^{-1} day^{-1}	
N_2O flux from $^{15}NH_4{}^{14}NO_3$	1.91	0.70
N_2O flux from $^{14}NH_4{}^{15}NO_3$	0.98	0.37

At 1 DAF, gross nitrification (171 g N tree^{-1}) exceeded dissimilatory nitrate reduction to ammonium (DNRA; 16.2 g N tree^{-1}). Gross mineralization (15.5 g N tree^{-1}) was lower and NH_4^+ consumption (116 g N tree^{-1}) and NO_3^- consumption (244 g N tree^{-1}) were greater than at 2 DAF. At 2 DAF, both DNRA (24.0 g N tree^{-1}) and gross mineralization (37.1 g N tree^{-1}) increased while gross nitrification (67.9 g N tree^{-1}), NH_4^+ (70.5 g N tree^{-1}) and NO_3^- (101 g N tree^{-1}) consumption decreased compared to 1 DAF. These results support the notion that fertilization stimulates oxidation and consumption of N within 1 DAF and that this system shifts progressively toward greater soil N supply from mineralization and soil N retention by DNRA within 48 hours. At 1 DAF, microbes assimilated more N than at 2 DAF and up to an order of magnitude greater than tree roots. Despite greater competition for N, peak $^{15}N_2O$ flux was observed at 1 DAF and was substantially greater from $^{15}NH_4{}^{14}NO_3$ compared to $^{14}NH_4{}^{15}NO_3$ (**Table 4**). We conclude that effective N management may be attainable from increased utilization of native soil N, increased retention of soil N, and inhibiting nitrification that leads to N losses from agricultural ecosystems.

Cited References and Smart Lab Publications:

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

Alsina, M. M., A. Borges, and **D. R. Smart**. *In press*. Spatiotemporal variation of event realated N_2O and CH_4 emissions during fertigation in a California almond orchard. Ecosphere.

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., **D. 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.

Bouwman, A. F., and L. J. M. Boumans. 2002. Modeling global annual N_2O and NO emissions from fertilized fields. Global Biogeochemical Cycles **16**:1080-1089.

Bremner, J. M. 1997. Sources of nitrous oxide in soils. Nutrient Cycling in Agroecosystems **49**:7-16.

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

Carlisle, E., K. L. Steenwerth, and **D. R. Smart**. 2006. Effects of land use on soil respiration: Conversion of oak-woodlands to vineyards. Journal of Environmental Quality **35**:1396-1404.

Freney, J. R. 1997. Strategies to reduce gaseous emissions of nitrogen from irrigated agriculture. Nutrient Cycling in Agroecosystems **48**:155-160.

Halvorson, A. D., S. J. Del Grosso, and F. Alluvione. 2010. Tillage and inorganic nitrogen source effects on nitrous oxide emissions from irrigated cropping systems. Soil Science Society of America Journal **74**:436-445.

Linquist, B., K. J. van Groenigen, M. A. Adviento-Borbe, C. Pittelkow, and C. van Kessel. 2012. An agronomic assessment of greenhouse gas emissions from major cereal corps. Global Change Biology **18**:194-209.

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 N_2O in a Mexican wheat system using ^{15}N. Ecological Applications **10**:506-514.

Scheer, C., R. Wassmann, K. Kienzler, N. Ibragimov, J. P. A. Lamers, and C. Martius. 2008. Methane and nitrous oxide fluxes in annual and perennial land-use systems of the irrigated areas in the Aral Sea Basin. Global Change Biology **14**:2454-2468.

Schellenberg, D. L., M. M. Alsina, S. Muhammad, **C. M. Stockert**, M. W. Wolff, B. L. Sanden, P. H. Brown, and **D. R. Smart**. 2012. Yield-scaled global warming potential from N_2O emissions and CH_4 oxidation for almond (*Prunus dulcis*) irrigated with nitrogen fertilizers on arid land. Agriculture Ecosystems and Environment **155**:7-15.

Smart, D., and A. Bloom. 2001. Leaves emit nitrous oxide during nitrate assimilation. Proceedings of the National Academy of Sciences of the United States of America **98**.

Smart, D., and P. J. 2005. Changes in soil CO2 respiration following precipitation onto dry soils: An investigation of elevated CO2 using Mediterranean plants. Applied Soil Ecology **28**:247-257.

Smart, D. R., **M. M. Alsina**, M. W. Wolff, M. G. Matiasek, **D. L. Schellenberg**, J. P. Edstrom, P. H. Brown, and K. M. Scow. 2011. Nitrous oxide emissions and water management in

California perennial crops. Pages 227-255 *in* L. Guo, A. S. Gunasekara, and L. L. McConnell, editors. Understanding Greenhouse Gas Emissions from Agricultural Management. American Chemical Society, Washington, DC.

Smart, D. R., J. M. Stark, and V. Diego. 1999. Resource limitations to nitric oxide emission froma sagebrush-steppe ecosystem. Biogeochemistry **47**:63-86.

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

Suddick, E., K. M. Scow, W. R. Horwath, J. E. Jackson, **D. R. Smart**, J. Mitchell, and J. Six. 2010. The Potential for California Agricultural Crop Soils to Reduce Greenhouse Gas Emissions: A Holistic Evaluation Advances in Agronomy **107**:123-167.

Suddick, E. C., K. Steenwerth, G. M. Garland, **D. R. Smart**, and J. Six. 2011. Discerning agricultural management effects on nitrous oxide emissions from conventional and alternative cropping systems: A California case study. Pages 203-226 *in* L. Guo, A. S. Gunasekara, and L. L. McConnell, editors. Understanding Greenhouse Gas Emissions from Agricultural Management. American Chemical Society, Washington, DC.

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 America 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 & Environment **116**:209-215.

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