Optimizing the Use of Groundwater Nitrogen (NO_3): Efficacy of the Pump and Fertilize Approach for Almond

Project No.: **14-PREC6-Smart**

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Objectives:

The overarching objective is to quantify and demonstrate the efficacy of irrigation water nitrogen (N) as a component of orchard N budgets ("pump and fertilize", P&F), and to contrast the P&F approach with "advanced grower practice" (split applications targeted to N demand and root proliferation, AGP) and high frequency low N concentration fertigation (HFLC). The objectives being pursued under this agreement include:

1) Establish research and demonstration orchards for "Advanced Grower Practice" (AGP) and "High Frequency Low Nitrogen Concentration" (HFLC, 'spoon feed') as contrasted with "Pump and Fertilize" (P&F) nitrogen (N) management in pistachio and/or almond within two "Hydrogeologically Vulnerable Areas" (HVAs).
2) Utilize and validate recent developments in yield and nutrient budget N management, early season sampling and yield estimation (AGP) to describe best management practices and contrast those practices with P&F N management treatments.
3) Characterize key biological and physical parameters relevant to the P&F concept (concentration dependent uptake, root distribution and activity, phenology of uptake, seasonal plant-soil N balance, soil NO_3^- movement etc.).
4) Establish proof of concept for use of stable isotopes of $\delta^{15}N$-NO_3^- in N tracing under P&F practices.
5) Develop and grounds validate decision support models (including HYDRUS) to assist growers with optimal management of groundwater nitrogen (NO_3^-).
6) Demonstrate and proactively extend developed results, technologies relevant to on-site self-assessment and BMP's to growers.

Interpretive Summary:

Over 30 million California residents (about 85%) rely partially or fully on groundwater as a source of drinking water (SWRCB, 2012). Nearly 2,600 California communities rely on about

8,400 community public supply wells as the main source of their drinking water. Among these, 1,662 public supply wells in 682 California communities are contaminated, and in one-third of these communities due to nitrate pollution alone (206 communities with 452 nitrate contaminated wells). This does not include private domestic households or households on state-small and local public water systems (2-14 connections), of which as many as 40% may be contaminated with nitrate (Boyle et al., 2012). In regions with predominantly agricultural land use, such as the Central Valley and the Salinas Valley, over 90% of groundwater nitrate pollution is estimated to originate from agricultural lands (Harter et al., 2012). Improved water and nutrient management practices would lead to significantly lower groundwater nitrate (NO_3^-) pollution. These practices must also account for non-fertilizer sources of nitrogen, such as irrigation water nitrogen and soil amendment nitrogen, (Dzurella et al., 2012). Few studies have considered managing nitrate in irrigation water ("pump and fertigate"), but in one example it was found that replacement of commercial fertilizer with irrigation water NO_3^- was effective at a 1:1 ratio or better (King et al., 2012). There is a need to develop an understanding of the utility of groundwater nitrate as a source of N for nut crops and to field demonstrate this practice so that guidelines for grower implementation can be developed and extended.

Our primary objective during the first half of 2015 was to continue monitoring leaching and N-mass balance for a second season under proposed best management practices by applying nutrient budget N management and to describe and contrast those practices with 'Pump and Fertilize' treatments. Prior to the beginning of the growing season, the growers in all three orchards planned the N budget for the year based on the Almond Nitrogen Model accounting for groundwater NO_3^--N concentration (P&F). N-fertilizer was applied as planned and leaf samples indicated there was no need to modify the N-budget mid-season. During the 2015 growing season N-fertilizer (UAN 32) was applied at the end of irrigation/fertigation events while during 2014 it was applied in the middle of irrigation. Differences were observed in the temporal trends of the NO_3^--N concentrations at 180 cm and 290 cm (potential leachable NO_3^-) during 2014 and 2015 growing seasons. The observed differences in NO_3^--N showed that fertigation at the beginning/middle of an irrigation cycle tends to increase seasonal NO_3^- leaching, while fertigation events at the end of the irrigation cycle reduced the potential for NO_3^- leaching. Pre-bloom and post-harvest flood irrigation events led to deep wetting (>300 cm) and downward flushing of NO_3^--N deep into the vadose zone. Comparison between the total N loads in the soil profile based on soil extractions down to depth of 3 m prior to the beginning of the 2014 and 2015 growing seasons, suggested minimal, if any, N uptake from the deep profile (>1.5 m). Soil extraction indicated the persistence of high N-loads in the subsurface. Differences were observed between the soil extractions and the pore-water samples from similar sites, suggesting that there were two main N-phases in the soil, one mobile phase and another immobile. The differences between the two sampling methods indicated that most of the applied N-fertilizer stays in the mobile phase and therefore is more likely to propagate deep into the vadose zone and contaminate groundwater. Based on water mass balance of one orchard, the average leaching in the almond orchard over a growing season was 12±8 cm, and ranged from 0 to 24.5 cm. N-mass balance showed that during the 2014 growing season 95 – 152 and 44 – 52 lb.-N acre^{-1} were not accounted for in the almond and pistachio orchard, respectively. Based on the water and N mass balance, NO_3^--N concentrations in the water leaching below the almond orchard should be 89 – 142 mg/L. The statistical approach of principal component analysis (PCA) was used to evaluate the correlations between NO_3^--N concentrations at depth of 290 cm (427 water samples) and the principal factors that may influence it. In all the fertigation strategies (AGP, HFLC and P&F) NO_3^--N concentrations were positively correlated with the timing within an irrigation event of fertilizer injection and total length of irrigation. NO_3^--N concentrations were negatively correlated with the presence and thickness of hard pan in the subsurface and flood irrigation. The correlations emphasize the need for fertilizer application towards the end of an irrigation event, and the need for short term consecutive irrigations to keep the fertilizer and water in the active root zone (<1.5 m). The presence, depth and width of the hard pan, the time of fertigation and the length of the irrigation following the fertilizer injection had the highest contribution to explanation of variability in the data. These data highlight that water management may be critical rather than any single proposed N best management practice.

Materials and Methods:

<u>Objective 1.</u> Establish research and demonstration orchards for P&F as well as AGP and HFLC N management in almond within two “Hydrogeologically Vulnerable Areas” (HVAs).

Three orchards were established in two HVAs, one located in the Madera groundwater basin between the Madera Water Bank (North) and the San Joaquin River (South), the municipality of Madera (East) and the San Joaquin River (West). Matt Andrew of ATB Growers, a cooperative that encompasses more than 2,100 acres of almond and pistachio, is the grower and contact person. Using ground water depth information taken from Department of Water Resources and Madera Irrigation District databases, we established two orchards (one pistachio, one almond) where the fertilizer strategies of AGP, P&F and HFLC were tested and contrasted during the 2014 and 2015 growing seasons. We have established fully randomized complete blocks designs for the two orchards, the orchard treatments were carried through to harvest in 2014 and 2015 and we plan to carry the Madera treatments through the 2016 growing season.

We continued to identify and work with a new grower in the Modesto Groundwater Basin. This represents a delayed component of the project and has involved an extensive search for a grower/cooperator within an HVA area consisting of ‘shallow’ depth to groundwater (e.g. 25-35 ft.) and sandy or sandy loam type soils. We anticipate conducting a soil survey and installing groundwater monitoring wells shortly after the 2015 harvest (September).

We have entered into initial agreement with the grower and are planning a generalized soil survey during September 2015 for proposed establishment of GW monitoring wells (**Figure 1**).

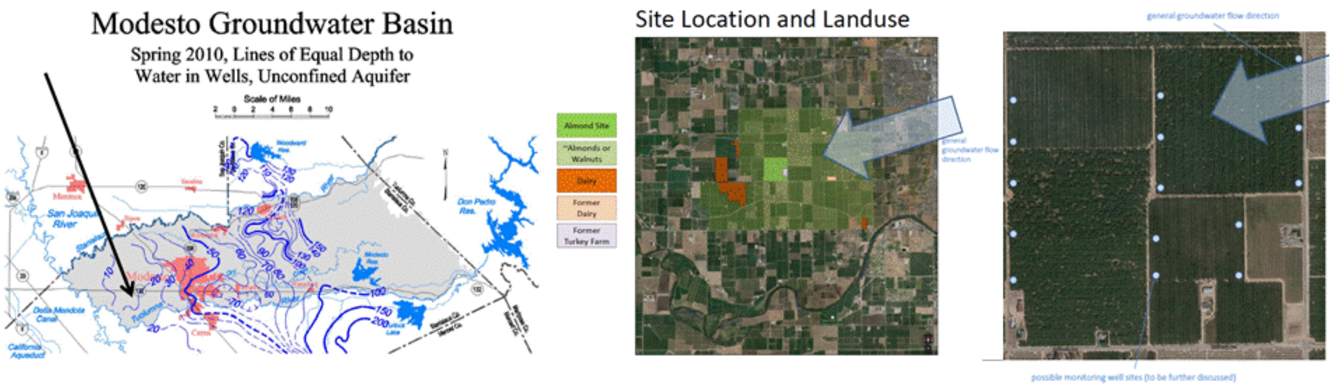

Figure 1: Location in the Modesto Groundwater Basin (A), land use patterns (B) and preliminary plan for network of groundwater monitoring wells (C) associated with continuous high frequency P&F fertilizer N management.

<u>Objective 2.</u> Utilize and validate recent developments in yield and nutrient budget N management, early season sampling and yield estimation to prescribe best management practices and contrast those practices with P&F nitrogen management treatments.

In each orchard, eight sites were instrumented with an access tube for neutron probe, five root zone and deep solution samplers, four deep tensiometers, and five 5TE probes (Decagon, Pullman, WA, USA). The installed sensors monitor processes in and below the root zone. The depth at which the probes were installed were based on observation in three soil pits (3 m depth) excavated to determine rooting depth (**Figure 2**). Dositrons were installed at the high frequency subplots to facilitate nitrogen (N) additions, and a subcontract developed with Dr. Sharon Benes at Fresno State University to engage an irrigation management intern to work with grower/cooperators to insure N application amounts were accurate.

<u>Objective 3.</u> Characterize key biological and physical parameters relevant to the P&F concept (concentration dependent uptake, root distribution and activity, phenology of uptake, seasonal plant-soil N balance, soil NO_3^- movement etc.

Nitrogen concentrations in the subsurface soils were estimated prior to and through the growing season. Nitrogen concentrations prior to the growing season indicated accumulation of NO_3^--N in the subsurface (>150 cm). The high concentrations in the deep profile below the root zone, suggested there is a risk for groundwater contamination by NO_3^- leaching. Data being processed for the current season and gathered during the upcoming season should reveal whether or not treatment differences exist among AGP, P&F and HFLC but there is not currently sufficient data to make any definitive statements.

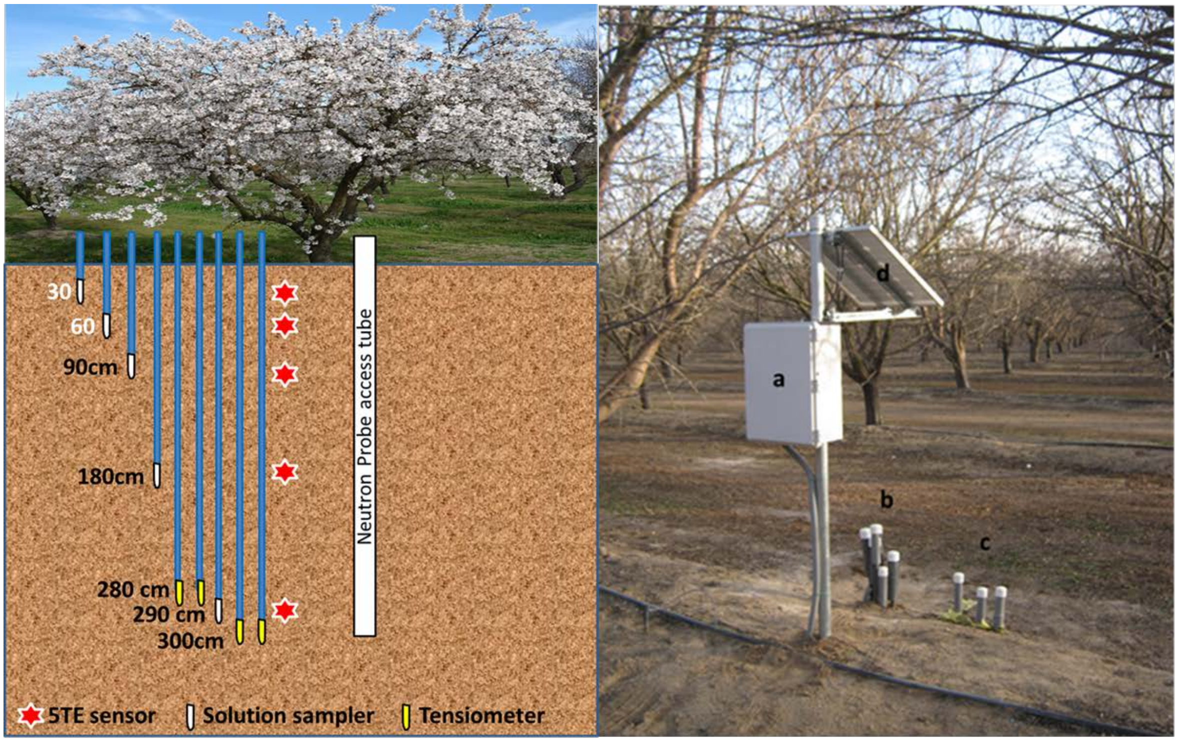

Figure 2: The basic set-up of the intensively monitored trees (left panel), and the way it appears in the almond orchard within Madera HVAI (right panel). (a) Housing for the electronics, (b) tensiometers and deep solution samplers (280 – 300 cm below land surface (bls)), (c) shallow solution samplers (30, 60, 90 cm bls), and (d) solar panel to charge the battery powering the electronics.

<u>Objective 4.</u> Establish proof of concept for use of stable isotopes of $\delta^{15}N\text{-}NO_3^-$ in N tracing under P&F practices.

To assess the $\delta^{15}N$ and $\delta^{18}O$ of nitrate (NO_3^-) in ground water and the vadose zone, the isotopic ratios of $^{15}N/^{14}N$ and $^{18}O/^{16}O$ are quantified by converting the solution NO_3^- into nitrous oxide (N_2O) in an oxygen free environment (zero grade N_2). N_2O in the head space then serves as the analyte for continuous flow gas chromatography (GC) isotope ratio mass spectrometry (IRMS). A culture of denitrifying bacteria (*Pseudomonas chlororaphis* and *P. aureofaciens*) is used in this headspace analysis for enzymatic conversion of NO_3^- to N_2O, which follows the reaction pathway shown in equation 1:

$$NO_3^- \rightarrow NO_2^- \rightarrow NO \rightarrow \tfrac{1}{2}N_2O \qquad \text{eqn 1}$$

Because the bacteria lack N_2O reductase activity, the reaction stops at N_2O, unlike most microbial denitrification reductions that go to completion at N_2. Once the conversion is complete, the zero grade N_2 containing microbially derived N_2O is extracted from the vial and separated from water vapor by an inline nafion membrane drier, and from CO_2 with a layered Mg $(ClO_4)_2$/Ascarite trap. N_2O focusing is achieved by trapping the N_2O in a small-volume trap immersed in liquid nitrogen (-196°C). After the N_2O is warmed and released, it is purified by gas chromatography (GC) before being carried by helium to the IRMS via an Agilent GS-Q capillary column (30m x 0.32 mm, 40°C, 1.0 mL min^{-1}). This column separates N_2O from any residual CO_2. The IRMS is a continuous flow isotope-ratio mass spectrometer (CF-IRMS). It has a universal triple collector, consisting of two wide Faraday cups with a narrower center cup for quantifying ratios of 44:45, 44:46 and 45:46 N_2O. The ion beams from these *m/z* values are as follows: *m/z* = 44 = N_2O = $^{14}N^{14}N^{16}O$, *m/z* = 45 = N_2O = $^{14}N^{15}N^{16}O$ or $^{14}N^{14}N^{17}O$, and *m/z* = 46 = N_2O = $^{14}N^{14}N^{18}O$. The ^{17}O contributions to the *m/z* 44 and *m/z* 45 ion beams are accounted for before $\delta^{15}N$ values are reported.

Objective 5. Develop and ground validate decision support models (including HYDRUS) to assist growers with optimal management of groundwater nitrogen (NO_3^-).

The field gathered data on matric potential and water content from depths of 280 – 300 cm was used to generate in-situ retention curves for the deep soil at the different monitoring sites. RETC code (van Genuchten et al., 1991) was used with the parameterized models of van Genuchten (van Genuchten, 1980) to represent the soil water retention curve and the theoretical pore-size distribution models of Mualem and Burdine (Mualem, 1976) to predict the unsaturated hydraulic conductivity function from the gathered soil water retention data. The predicted unsaturated hydraulic conductivity parameters (α, n), along with the measured hydraulic gradient between 280 and 300 cm were used to calculate the daily unsaturated hydraulic conductivity (k(h)) and the Darcy flow equation to estimate the water flux below the root zone.

Results and Discussion:

Objective 1. Establish research and demonstration orchards for P&F as well as AGP and HFLC N management in almond within two "Hydrogeologically Vulnerable Areas" (HVAs).

Three orchards were established in two HVAs during 2013 (see Materials and Methods for details). One was located in the Madera groundwater sub-basin between the Madera Water Bank (North) and the San Joaquin River (South), the municipality of Madera (East) and the San Joaquin River (West). The second was established in an almond orchard in the Turlock Groundwater Basin.

Objective 2. Utilize and validate recent developments in yield and nutrient budget N management, early season sampling and yield estimation to prescribe best management practices and contrast those practices with P&F nitrogen management treatments.

Conducted nutrient budget N management, fertigations and early season leaf sampling for N-fertilizer adjustment to all three treatments (advanced grower practice – AGP, pump and fertilize – P&F and high frequency low-N concentration – HFLC). These tasks were completed in two HVAs consisting of three research orchards (pistachio and almond in the Madera Groundwater Sub-basin, almond in the Turlock Groundwater Basin). **Table 1** lists the quantities of N applied as of June of 2015.

Table 1. Nitrogen amounts applied to the orchards (to June 30th) during the 2015 growing season.

	UAN32 (lb. acre^{-1})		
Treatment	Almond Madera	Almond Turlock	Pistachio Madera
AGP	210	112	130
P&F	156	79	120
HFLC	126	42	80
Groundwater	10-30	60-90	10

Leaf analysis and yield – the first harvest of almond was gathered on August 11th and 12th. Pistachios were also harvested on September 14th. These data are still undergoing analysis for development of a nitrogen mass balance for the orchards and to determine relative nitrogen use efficiencies. Nonetheless, average yields of kernels per acre so far have not revealed any major differences between the AGP, P&F and HFLC treatments. In addition, mid-season (April) leaf N concentrations indicated there was no need for adjustment of the planned nitrogen input budgets.

Objective 3. Characterize key biological and physical parameters relevant to the P&F concept (concentration dependent uptake, root distribution and activity, phenology of uptake, seasonal plant-soil N balance, soil NO_3^- movement etc.

Nitrate-nitrogen (NO_3^--N) concentrations in the pore-water at and below the root zone in an almond and pistachio orchards were monitored over two consecutive growing seasons (2014 and 2015). Over a 1,000 samples were collected from the soil profile with more than 600 samples from depths of 1.8 and 2.8 m. The concentrations below the root zone at the almond and pistachio orchards ranged from <1 mg L^{-1} to over 550 mg L^{-1} and up to 2,500 mg L^{-1} (**Figure 3**). The mean concentrations below the root zone under the almond and pistachio orchards were almost one to two orders of magnitude, respectively higher than the drinking water standard of 10 mg/L NO_3^--N (**Table 2**).

Transport and Uptake Following Fertigation Events

In each growing season the AGP and P&F treatment subplots in the almond and pistachio orchards were fertigated with three and four split applications, respectively, while the HFLC treatment was fertigated twenty times. Pore-water sampled below the active root zone (>1.5 m), showed mixed responses to the fertigation events. During 2014 sharp increases in NO_3^--N concentrations were observed at 1.8 m across many sites, and at 2.9 m at some sampling sites. In contrast, during 2015 minimal increases in NO_3^--N concentrations were observed at depths of 1.8 and 2.9 m (**Figure 4**).

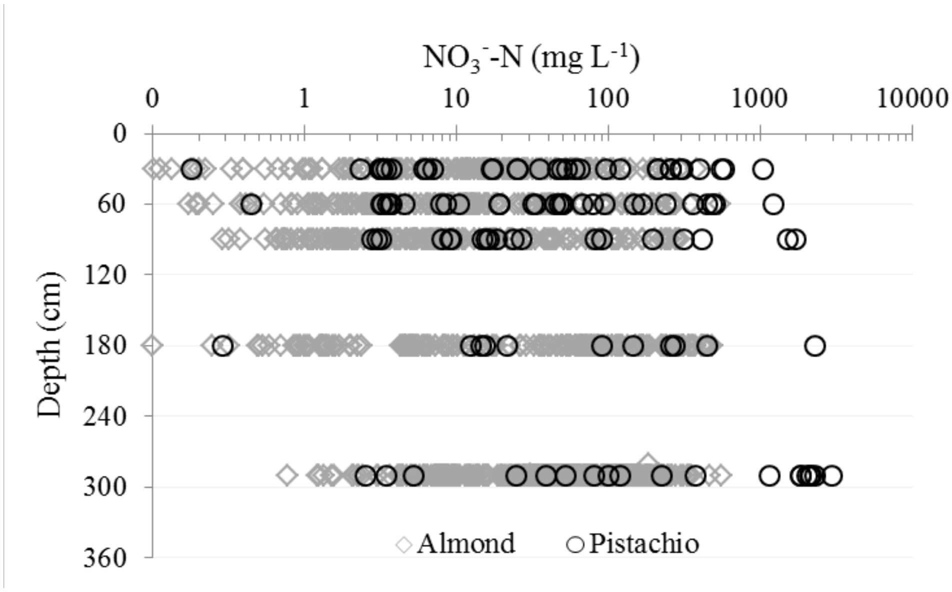

Figure 3. Nitrate-nitrogen (NO_3^--N) concentrations in pore-water samples from eight vadose zone monitoring sites in almond and pistachio orchards, each sampled during the 2014 and 2015 growing seasons.

Table 2. Mean and standard deviation of pore-water NO_3^--N concentrations (mg L^{-1}) by depth and tree crop.

	Sampling depth (cm)				
	30	60	90	180	290
Almond	37 ± 59	40 ± 78	38 ± 67	85 ± 116	73 ± 77
Pistachio	148 ± 229	142 ± 257	235 ± 498	322 ± 661	917 ± 1046

An exception to that trend was observed in two of the monitoring sites where increases were observed at 2.9 m but not at 1.8 m (**Figure 4**). The differences in the observed increases reflect the time of fertilizer application within an irrigation event. In 2014 at the AGP, P&F and HFLC treatment subplots UAN32 fertilizer was applied in the middle of a 48 h fertigation event, while in 2015 the fertilizer was applied at the end of the irrigation. Similar to the work of Gärdenäs et al., (2005) the observed differences in the NO_3^--N increases in 2014 and 2015 showed that fertigation at the beginning/middle of an irrigation cycle tends to increase seasonal nitrate leaching, while fertigation events at the end of the irrigation cycle reduced the potential for nitrate leaching. It is likely however, that gravimetric flow following a fertigation event at the end of an irrigation event would lead to some deep transport of the applied fertilizer, mainly due to less lateral distribution by capillary forces, as suggested by Cote et al. (2003). Additional downward flushing probably occurs with each successive irrigation event. This assumption is supported both by the long residence time of the fertilizer in soil (the estimated N-uptake rate of mature almond trees is <4 g-N-tree d^{-1}, D Schellenberg, unpublished data) and by the field observations. Examples of such deep transport is shown in **Figure 5**, where during 2015 at some locations, including HFLC, the NO_3^--N concentration at 290 cm increased during the season even though the fertilizer was applied at the end of each irrigation event. All of the above observations have suggested that in order to minimize NO_3^--N losses to deep drainage there is a need to apply the fertilizer towards the end of the fertigation event and to strive for short consecutive irrigation events. Such an approach would likely keep the water in the active root zone (<1 m), as suggested by Phogat et al. (2011) for almond.

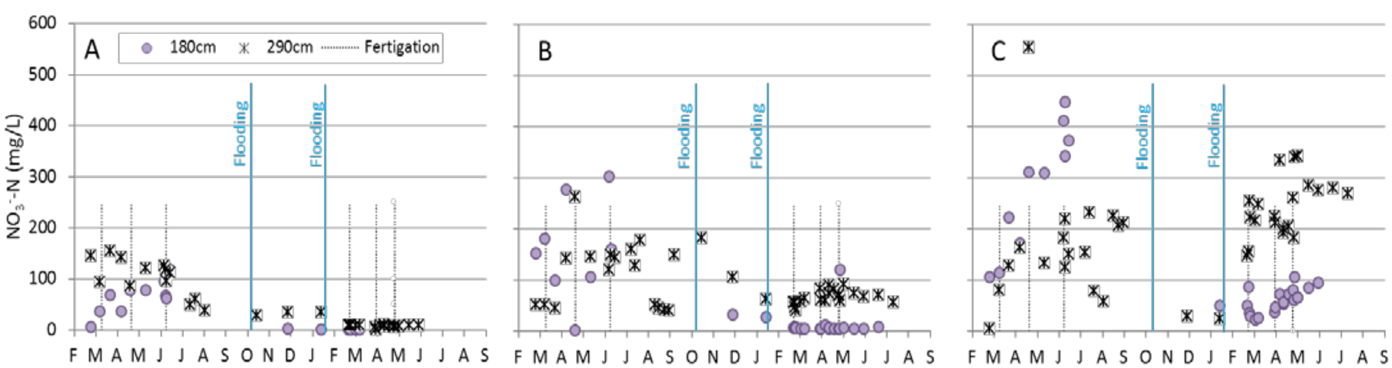

Figure 4. Temporal trends in NO_3^--N concentrations in the pore-water samples from a depth of 180 and 290 cm at three monitoring sites in one of the almond orchards.

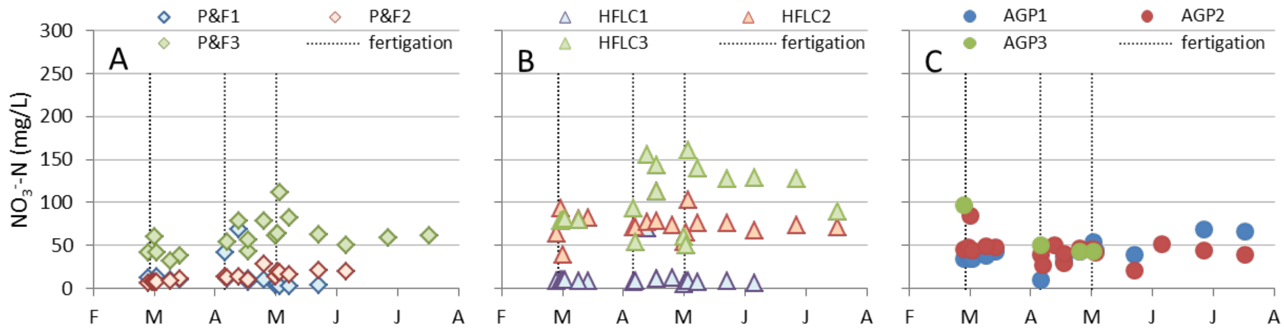

Figure 5. Nitrate-N concentrations in pore-water samples from depth of 290 cm taken throughout the 2015 growing season under three fertigation strategies for the almond orchard.

Nitrogen concentrations in porewater samples through the growing season varied temporally and spatially and ranged from 5 to 150 mg L^{-1} (ppm). So far, we have not been able to determine the cause for the variability and the subject warrants further study in 2015. In all locations the concentrations below the root zone were much higher than the maximal allowed values for drinking water (10 mg NO_3^--N L^{-1} irrigation water). The porewater concentrations are in agreement with the sediment extractions, and highlight a potential for groundwater contamination by leachates, especially in locations where hardpan or accumulation of fines did not occur in the subsurface

Objective 4. Establish proof of concept for use of stable isotopes of δ^{15}N-NO_3^- in N tracing under P&F practices.

The analysis of natural abundance of stable isotopes of nitrogen (δ^{15}N) and oxygen (δ^{18}O) of NO_3^- in irrigation water and porewater, as compared with N of leaf and kernel samples, indicated enrichment from depth of the porewater δ^{15}N-NO_3^- in the subsurface to values higher than that of the groundwater. The δ^{15}N values of organic-N in the kernels did not vary between treatments and suggested uniform mixing of groundwater N with N from fertilizer among treatments. Further analysis is needed to confirm these preliminary conclusions.

Objective 5. Develop and ground validate decision support models (including HYDRUS) to assist growers with optimal management of groundwater nitrogen (NO_3^-).

The fluxes calculated by the above described method did not provide good leaching estimates. We believe the main sources of error in the estimates were due to values of saturated hydraulic conductivity and calculations not being constrained by the daily water balance. Nonetheless, even though the magnitude of the leaching estimates was inaccurate, the temporal trends were representative. Matric potential measurements indicated the soil reaches field capacity (-100 – -300 mbar; Nachabe, 1998) around mid-April. Following that, the deep profile starts to dry, and the hydraulic gradient reverses; thus, water starts flowing upwards from the deeper soil layers which is not unprecedented. Although most water uptake occurs in the upper 1 m of the profile, root water uptake by the % of deep roots can contribute to drying at > 1 m depth. This rapid drying results from the low water holding capacity of sandy soils, where small decreases in water content lead to large increases in matric potential. This effort contributes to modification of the HYDRUS model (Šimůnek et al., 1998) to enable better leaching estimates to account for the daily water balance (irrigation vs. transpiration) and for the soil layering (high/low hydraulic conductivity). Simulations by the modified HYDRUS model incorporate effective hydraulic properties of soil horizonation. Once leaching estimates are optimized for these factors, nitrate transport in the soil will be better simulated by HYDRUS.

Objective 6. Demonstrate and proactively extend developed results, technologies relevant to on-site self-assessment and BMP's to growers.

The following represents a partial list of outcomes achieved by attending grower meetings and publishing or presenting proceedings/posters/advisories in conjunction with the meetings.

Schellenberg, DL, MW Wolff, MM Alsina, CM Stockert and DR Smart (2013) Net Primary Productivity and Greenhouse Gas Exchanges for Major California Perennial Crops. Farming for the Future: California Climate and Agriculture Summit, February 21st, California Climate Action Network (Cal-CAN), Davis, CA, >200 attendees.

Smart, DR, PH Brown, G Ludwig (2013) Nitrogen Use Efficiency of California Almond Orchards, USDA Central Valley Nitrogen Efficiency Conference, June 6th, Modesto CA, 40+ attendees

Wolff, MW, DL Schellenberg, A Olivos, BL Sanden, PH Brown and DR Smart (2013) Reducing Mobile-N Loss from Fertigation: Field and Modeling Approaches. Improving Nitrogen Use Efficiency in Crop and Livestock Production Systems, Soil Science Society of America, August 13-15, Kansas City MO, >200 attendees.

Salas, W, DR Smart, J Kimmelshue (2013) DNDC Modeling Update, Sustainability Strategic Meeting, Oct 31st, 12 attendees.

Smart, DR (2013) Mitigation of Reactive N Mobilization (N_2O and NO_3^-) Using Injected, High Frequency Low Nitrogen Fertigation (HFLN). Almond Board of California Annual Meeting, Dec 3rd-5th, Sacramento CA, 2,555 attendees.

Smart DR (2013) Optimizing the Use of Ground Water Nitrogen in Nut Crops. Almond Board of California Annual Meeting, Dec 3rd-5th, Sacramento CA, 2,500+ attendees.

Smart, DR (2013) Mitigation of Reactive N Mobilization (N_2O and NO_3^-) Using Injected, High Frequency Low Nitrogen Fertigation (HFLN). Almond Board of California Annual Meeting Proceedings/Research Updates.

Smart DR (2014) Sustainable Management of the Root Zone, Sustainable Agriculture Expo, San Luis Obispo CA November 17-18th, >400 attendees.

Baram S, M Read, CM Stockert, T Harter, P Brown, JW Hopmans DR Smart (2014) Optimizing the Use of Groundwater Nitrogen (NO_3^-): Efficacy of the Pump and Fertilize Approach for Almond. Almond Board of California Annual Meeting, Dec 9th-11th, Sacramento CA, 2,925 attendees.

Smart, DR, S Baram, M Read, CM Stockert, T Harter, P Brown, JW Hopmans, (2014) Optimizing the Use of Groundwater Nitrogen (NO_3^-): Efficacy of the Pump and Fertilize Approach for Almond. Conference Proceedings/Research Updates.

Dabach, S, DR Smart, M Read, C Stockert (2014) Evaluating Nitrogen Management Strategies to Minimize Greenhouse Gas Emissions from California Almond Orchards. Almond Board of California Annual Meeting, Dec 8-10th, 2,925 attendees.

Smart, DR, S Dabach, M Read, C Stockert (2014) Evaluating Nitrogen Management Strategies to Minimize Greenhouse Gas Emissions from California Almond Orchards. Almond Board of California Annual Conference Proceedings/Research Updates.

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