A. Project Information:

Report Type: Final

Time Period Covered: October 1, 2012 to December 31, 2016.

Project Full Title: Optimizing the Use of Groundwater Nitrogen for Nut Crops.

FREP Grant No: 12-0454-SA.

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B. Objectives:

Overarching Objective:

The overarching objective being pursued under the proposed investigation contributes to a multidisciplinary investigation funded by the California Department of Food and Agriculture (CDFA) Fertilizer Research and Education Program (FREP) that will answer a number of questions relevant to the "pump and fertilize" (P&F) approach to groundwater NO_3^- management. The objectives being pursued under this agreement include:

1) Establish research and demonstration orchards for "Advanced Grower Practice" and "Pump and Fertilize" nitrogen (N) management in pistachio and 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 to describe best management practices and contrast those practices with 'Pump and Fertilize' N management treatments.

3) Characterize key physical parameters relevant to P&F concept, mainly soil NO_3^- movement inot the potentially leachable NO_3^- pool.

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 ground validate decision support models (including Hydrus) versus N mass balance 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.

C. Abstract:

During the first half of the project we monitored yields, NO_3^- leaching rates and N-mass balance under best management practices (BMPs) of High Frequency Low N Concentration (HFLC, spoonfeed), applying nutrient budget N management as described by the Almond Board of California's nitrogen model (Almond Nitrogen Model, 2014, Advanced Grower Practice, AGP) and to describe and contrast these practices with 'Pump and Fertilize' (P&F) N management treatments (subtracting of groundwater N from the overall budget). Prior to the beginning of each growing season grower/cooperators planned the N budget for the year based on the Almond Nitrogen Model accounting for groundwater NO_3^- concentration in the P&F treatment. N-fertilizer was applied as planned and leaf samples indicated that there was no need to modify the N-budget mid-season. This was a highly successful endeavor of the project and showed no differences in yield between the three treatment approaches to N management.

The second objective during 2014, 2015 and 2016 was to estimate water and N losses below the root zone at the orchard scale. Thus, a 3-yr study was conducted to explore nitrate (NO_3^-) leaching below the root zone of an almond and a pistachio orchard. Temporal changes in water content, pore water NO_3^- concentrations and soil water potential were monitored within and

below the root zone to a soil depth of 3 m at eight sites, which well represented spatial variation in soil profiles within California nut crop orchards. Large spatial and temporal variability in water flow and N transport dynamics were observed which posed significant challenges to accurately estimate N losses form the orchards. NO_3^- concentrations below the root zone ranged from <1 mg L^{-1} to more than 2400 mg L^{-1} (almond), and up to 11,000 mg L^{-1} (pistachio), with mean concentrations of 326 and 4631 mg L^{-1}, respectively. Orchard monthly average NO_3^- concentrations below the root zone ranged from 225 to 710 mg L^{-1} with mean annual concentration of 468, 333 and 38 mg L^{-1} for the 2014, 2015 and the 2016 growing seasons, respectively, although the 2016 growing season did not include post-harvest flood events as well as there were issues associated with extracting lysimeter samples from dry soils. We used the annual N-buildup (applied-N minus removed-N) as a reference to all of our calculations. Despite the huge variability in pore water NO_3^- concentration between sites, the larger spatio-temporal scale N-losses estimated at the annual orchard scale from surface N mass balance, vadose zone based water content of N mass balance, flow calculations, and HYDRUS modeling were all within the same order of magnitude (80–240 kg N ha^{-1} y^{-1}). All methods indicated that most of the N-loss occurred early in the growing season (February–May) when fertilizer was applied to wet soil profiles. Simple mass balance (i.e., N load applied minus N load removed) provided a good proxy of the annual N accumulation in the soil profile at the orchard scale. Reduction of N losses at the orchard scale would require alternative fertigation and irrigation practices to decrease the difference between the N load removed and the N load applied to orchards.

D. Introduction

The proposed research tested two easily adaptable best management practices of fertilizing micro-irrigated nut crops with N to diminish reactive N mobilization (mainly N_2O and NO_3^-) and contrasted these with P&F N management. Reactive N forms have several environmental consequences including ground water NO_3^- contamination The fundamental basis of this proposal was to bring together a multi-disciplinary team of scientists to intensively monitor a suite of California nut crops under pump and fertilize (P&F) nitrogen (N) management. The problem of mobilization of reactive nitrogen into air and water is currently the most important subject areas with respect to environmental sustainability for California agriculture and multi-disciplinary approaches will be needed to help resolve this problem. Nitrate (NO_3^-) is the primary contaminant of well waters and is extensively found in tapped aquifers in California's Central Valley (Viers et al. 2012). Nitrate contamination of water is reported to be "overwhelmingly the result of crop and animal agricultural activities" (Viers et al. 2012) and particularly the application of synthetic fertilizers to irrigated crops. The problem addressed in this proposal was whether or not P&F (eg. Viers et al. 2012, Table 9 p. 70) was a feasible mitigation option for growers of California's N intensive nut crops which currently represent over 30% of California's irrigated and fertilized acreage (Smart et al. 2011). We did this by bringing to the same table the highest degree of multidisciplinary intellect in tree nutrition (Brown), nitrogen loss (Smart), NO_3^- hydrology (Harter) and vadose zone modeling (Hopmans).

The P&F approach rests upon the assumption that nut crops can absorb and assimilate NH_4^+-N and NO_3^--N from dilute solutions and sustain economic production. The first six month of the project (October 2012 to June 2013) identified grower cooperator sites with shallow ground water tables, soils with high infiltration rates and ground water sources contaminated with NO_3^-. The project was timely because the State Water Control Board released its

Interagency Task Force Report, “Addressing Nitrate in California’s Drinking Water”, and a response to Senate Bill SBX2_1. This report identified Agricultural N use as the primary source of NO_3^- contamination and called for immediate solutions. This project proposed to examine one such preventative solution.

An initiative was funded and developed with the Almond Board of California (ABC) and grower friendly educational materials were disseminated. Understanding N_2O emissions and mitigation measures were identified as a critical need. This project represents a test of a cost effective means identified to help diminish GHG emissions with a stronger focus on N-intensive nut crops like almond. The approach, HFLN fertilizer applications targeted to tree and vine N demand, can be rapidly adopted by growers and has no issues of permanence. This project’s modeling exercises provided sensitivity analyses allowing the project team to identify the above, alternative and innovative methods for mitigation of NO_3^- leaching to groundwater in perennial crops. The ABC has funded parallel projects and modeling efforts with UCD for the N-intensive nut crops. The ABC is committed to developing workshops and promoting a self-assessment process to reduce NO_3^- leaching.

E. Work Description:

Tasks Achieved

The following outlined tasks were achieved during 1st October 2012 through December 31st 2016:

a. Tasks 1, 2, 3 and 4 – Almond orchard sites were located near Madera and Turlock with site characteristics (ground water depth of 60-100 ft., sandy and sandy loam soils) non-consistent with establishing connectivity between vadose zone N monitoring with first encounter of below root zone leachable NO_3^- with first encounter with groundwater (GW). We have now established a new site near Modesto with the characteristics of 25+ feet to capture connectivity between vadose zone and first encounter with groundwater over sandy and sandy loam soils. Nitrous oxide emissions measurements were carried out during all three seasons but are not included in this report (funded by Almond Board of California).

b. Tasks 5 and 6 – We conducted nutrient budget N management, fertigation and early season leaf sampling and N-loads adjustments to all three treatments (common advanced growing practice – AGP, pump and fertigate – P&F, high frequency low-N concentration – HFLC) at the two research orchards in Madera (pistachio and almond), 2014, 2015 and 2016 in Madera California.

c. Task 7 – The ground penetrating radar exercises were not deemed necessary following the intensive soil survey conducted in 2013.

d. Task 8 – Determine root distribution patterns using trench wall profiles. Further, characterize root distributions at the field sites being used for the GW monitoring wells. This task was carried out in 2013 for the intensively monitored experimental orchards.

e. Task 9 – Collected and analyzed for nitrate (NO_3^-) and total nitrogen (TN) content more than 250 pore water samples (almost weekly) from the vadose zone down to 300 cm below the surface (100 cm below the effective rooting depth). In addition we gathered soil samples from nine sites within orchard sites prior to the beginning of the 2014 and 2016 growing seasons to evaluate changes in the soil N-pool between seasons.

f. Tasks 10 and 11 – We will conduct preliminary site sampling and mapping to guide installation of GW monitoring wells. The GW research sites will be equipped with appropriate groundwater monitoring wells. The specific characteristics of the wells will be dependent on soil profile characteristics and depth to GW at each candidate site. Tasks 10 and 11 are going to be carried out in the new site near Modesto.

g. Tasks 12 and 13 – We estimated leaching under the orchards using field gathered data using modeling exercises in MATLAB, HYDRUS and RETC codes (PC Progress, Czech Republic). The simulations were compared to N budgets and mass balance estimates.

h. Task 14 – Present the first results and experimental principles and project goals at grower and other stakeholder meetings. (see below)

i. Task 15 – In collaboration with Almond Board and Pistachio Research Committee and Farm Advisors from relevant districts, organize 2 or more “field days” to present the new findings to growers, explain how to use the developed models for nutrient decision, illustrate and demonstrate P&F approach, and present preliminary outcomes. Task 15 was not carried out as a consequence of limited field space and accompanying concerns of the grower/cooperators.

j. Task 16 – Coordinate web and paper publications in grower and peer reviewed journals. Prepare technical summaries for use by commodity boards, water boards and other agencies (see below).

Approach

<u>Tasks 1, 2, 3 and 4</u> – Establish a groundwater (GW) monitoring site for gathering data on first encounter of potential leachable NO_3^- with the saturated zone.

Based on the soil survey results (Smart et al., 2015), which suggested N leaching to groundwater, we have reached an agreement with the grower that at the end of the 2016 growing season, a network of groundwater monitoring wells will be installed at the orchard (Figure 1). Nitrous oxide emissions were gathered in all three seasons and are not included in this report because it was not funded by CDFA FREP.

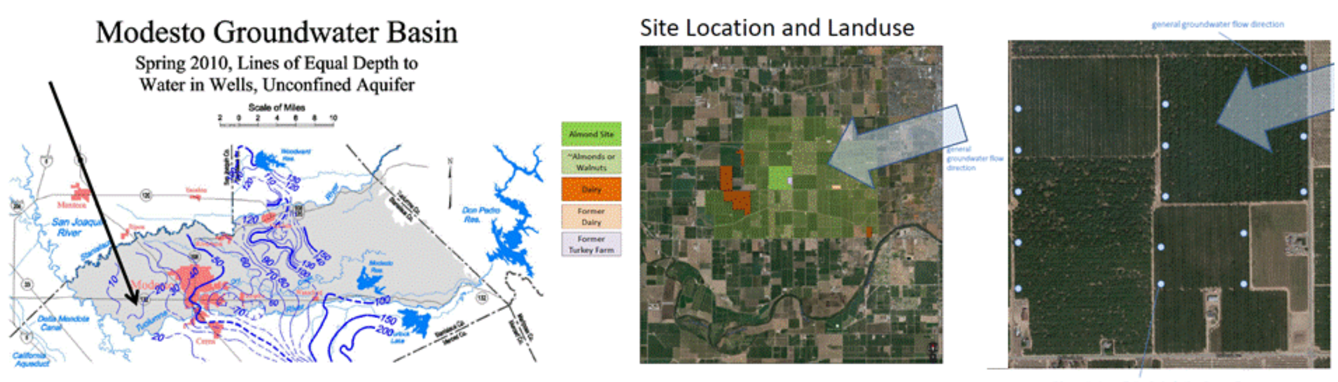

Figure 1*: Location in the Modesto Groundwater Basin (left panel), land use patterns (center pannel) and proposed plan for network of groundwater monitoring wells (right pannel) associated with continuous, high frequency pump and fertilize N fertilizer management.*

Tasks 5 and 6 – We established fertigation regimes that incorporated an 'Advanced Grower Practice' treatment that monitored leaf N status during the season, a 'Pump and Fertilize' regime (P&F) that incorporated and accounted for the concentration of groundwater N and finally a High Frequency Low N Concentration (HFLC) treatment that generally delivered approximately 20 units of N per irrigation (spoonfeed).

Following the farmer's request, the research site at Turlock was not used in the 2016 growing season. Prior to the beginning of each other growing season the nitrogen budget for the year was planned with the grower for the almond orchard using onsite data and the Almond Nitrogen Model (Almond Nitrogen Model, 2014) and for the pistachio orchard using the work of Siddiqui and Brown (2013) (Table 1). The operation of a new deep groundwater pump at the Madera site in April 2015 decreased the irrigation water NO_3^- concentration from 35 to 9 mg L^{-1} (Smart et al., 2015). Accordingly, to get a representative P&F treatment and duplicate the 2014 growing season, in the 2016 season NO_3^- has been added to the irrigation water as $Ca(NO_3^-)_2$ to get a concentration of 35 mg-NO_3^- L^{-1} in it. Irrigation water samples have been collected at the end of each irrigation event and, NO_3^- concentration in the irrigation water was analyzed to ensure that the concentrations resemble the 2014 NO_3^- concentrations. 'Dosatrons' were used to distribute the N-fertilizer loads according to seasonal uptake curve for almonds/pistachios (http://apps.cdfa.ca.gov/frep/docs/N_Almonds.html; http://apps.cdfa.ca.gov/frep/docs/N_Pistachio.html, respectively).

F. Data/Results:

Table 1 summarizes the nitrogen loads applied during 2016 as an example of the overall period in question at the orchards in Madera County. Leaf samples were collected in all seasons during mid-April, as recommended by the Almond Nitrogen Model, and total nutrient analysis was performed. The analysis indicated that there was no need to adjust the N-budget. At the almond orchard the grower applied most of the N-fertilizer earlier than planned, and with total N-load that was equivalent to an anticipated yield of 3000 lb.-kernel acre^{-1}, while the model predicted yield of 2648 lb.-kernel acre^{-1} (Table 1). The HFLC treatment at the pistachio site did not follow the planned schedule, due to miscommunication from the grower between our technical staff, and most of the fertilizer was generally applied early in the season (*cf* Table 1). Almond yields were gathered for all three treatments during the 2014, 2015 and 2016 seasons (Figure 2).

During the duration of these experiments, yields for the AGP, P&F and HFLC treatments were not statistically significantly different (Figure 2) and were all in an economically sustainable range of from approximately 2,600 to 3,200 lb. kernel per acre.

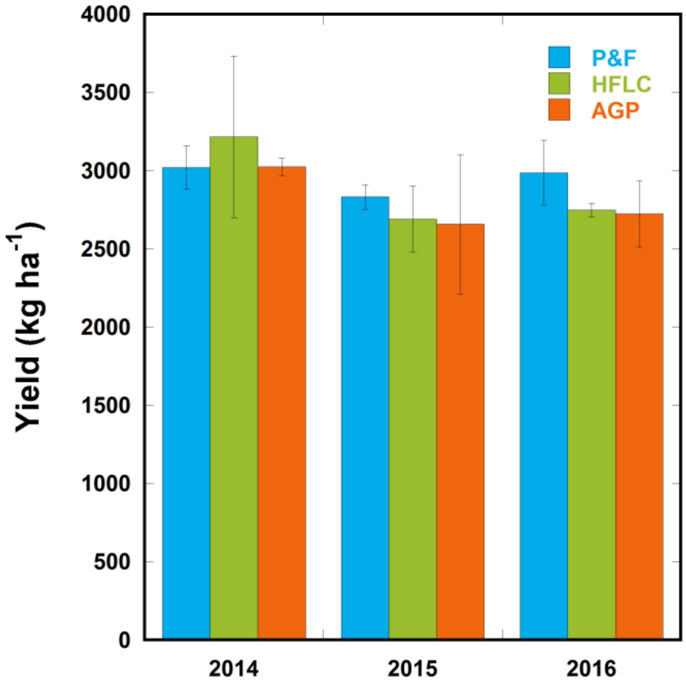

Figure 2: *Almond kernel yields (lb. acre^{-1}) for the P&F (blue), HFLC (green) and AGP (orange) treatments for the 2014, 2015 and 2016 growing seasons.*

Table 1. Planned and applied N-fertilizer loads to the AGP and P&F subplots at the almond and pistachio orchards during the 2016 growing season as an example of the duration of the experiment.

		AGP					P&F				
		Mar-Apr.	May-Jun.	Jun.-Jul.	Jul.-Aug.	Total	Mar-Apr.	May-Jun.	Jun.-Jul.	Jul.-Aug.	Total
Almond	Planned	69	92	69	0	**230**	48	64	48	0	**161**
	Applied	243	54	0		**297**	170	38	0		**208**
Pistachio	Planned	40	40	40	40	**160**	28	28	28	28	**112**
	Applied	39	47	47		**128**	39	43	33		**115**

		HFLC				
		Mar-Apr.	May-Jun.	Jun.-Jul.	Jul.-Aug.	Total
Almond	Planned	48	64	48	0	161
	Applied	55	66			121
Pistachio	Planned	28	28	28	28	112
	Applied	53	57			110

Task 9 – Measure soil water nitrogen and salts, and moisture levels at various depths. Parametrize all aspects needed for the HYDRUS model.

We monitored the temporal changes in the volumetric water content in the subsurface using continuous readings by 5TE sensors (Decagon Devices, WA USA) and bi-weekly readings using a neutron probe (Hydroprobe ,CPN, CA USA). To estimate the hydraulic gradient below the root zone we continuously monitored the matric potential below the root zone at 280 and 300 cm.

Soil samples were collected during February 2014 and February 2016 to determine the N content in the soil prior to the beginning of the growing season. Three locations were sampled at each treatment (P&F, AGP, HFLC) at 30 cm intervals. The sediment was extracted on 1:1 ratio with 2M KCl solution. The concentrations were compared to the concentrations measured a year (2014) and two years earlier (2015) and indicated that the total N (NO_3^-) in the vadose zone did not change in a statistically significant manner between growing seasons (Figure 3).

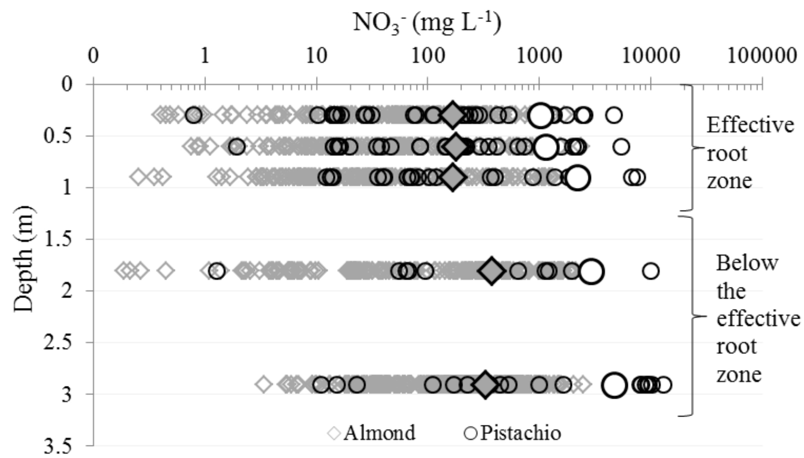

Figure 3: *Nitrate concentrations in pore water samples taken throughout the monitoring period 2014 – 2016.*

In addition to the statistical methods reported by our group in the past (Baram et al., 2016; Smart et al., 2015) which looked for correlations between the lithological profile and the fertigation regime we analyzed the spatial variability of pore-water NO_3^- concentration at depth of 2.9 m using semivariograms for the lag distance of γ(h) (Isaaks and Srivastava, 1990):

$$\gamma = \frac{1}{2N(h)} \cdot \sum_{i=1}^{N(h)} [z(x_i) - z(x_i + h)]^2 \qquad (1)$$

where *h* is the distance between two sampling sites (known as 'lag distance'), $z(x_i)$ is the measured NO_3^- concentration at site x_i and $N(h)$ is the number of pairs with the distance *h*. Using ArcGIS (Esri, 2011) kriging variogram model was fitted to the experimental variogram. The optimized semivariograms model found a lag distance of 8.5 m and indicated that the pore-water NO_3^- concentration were spatially correlated up to a distance of 60 m (range = 60 m), yet with a fairly high root mean square error (RMSE ~50 mg NO_3^--N L^{-1}). In the model lag distance of 20, 50 and 100 m indicated range of 115-130 m (Figure 4a).

On top of the semivariogram method we wanted to see if the spatial variability in NO_3^- concentration increased with distance between sampling points. For that purpose, coefficient of variation was calculated as the ratio between the standard deviation and the mean NO_3^- concentration for all the samples at a given distance (i.e. *N*(*h*) and *h*) was evident (Figure 4b).

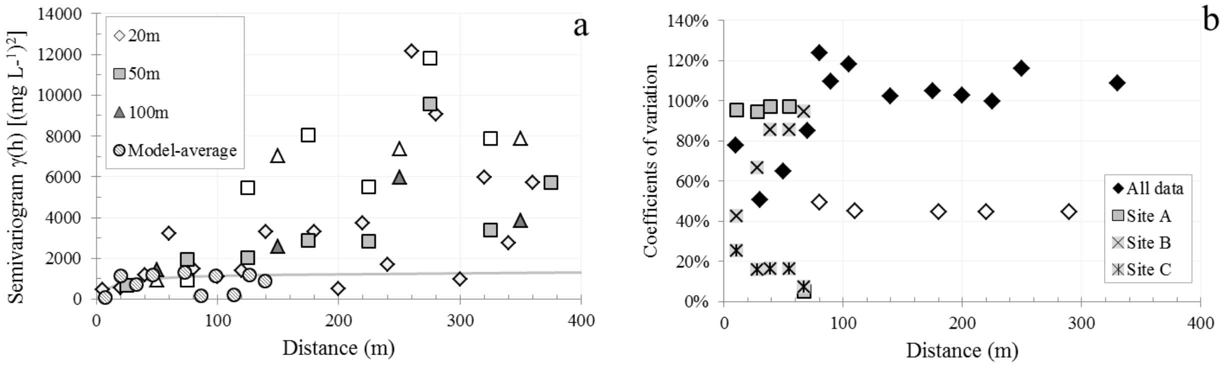

Figure 4. *Semivariogram (a) and coefficient of variation (b) of NO_3^--N concentration in relation to the distance between the pore-water sampling sites. Hallow and full symbols represent the 2014 and 2015 pore-water NO_3^--N concentrations, respectively. Continuous gray line represents the optimized semivariogram predicted by ArcGIS.*

Similar to all previous seasons, the orchard was flood irrigated prior to blooming, which led to deep wetting and downward leaching in the soil profile (Figure 5). Following the flood irrigation, from February through May, the soil profile down to 300 cm below the land surface dried, coinciding with a decrease in the hydraulic gradient between 280 and 300 cm (Figure 5).

<u>*Task 12 and 13*</u> – Run HYDRUS simulations with the inputs derived from current Almond Board funded project. Couple HYDRUS model outputs with nutrient budget outputs utilizing an existing optimization model (MATLAB).

During the first half of 2016 we focused on using the field gathered data over all three growing seasons to estimate the water flux and N losses through leaching below the root zone. We compared between three metrics and modeling exercises: (i) mass balance, (ii) Darcy model method, and (iii) inverse modeling using Matlab modified HYDRUS. Provided here is a detailed description of the approach we used along with the results and conclusion.

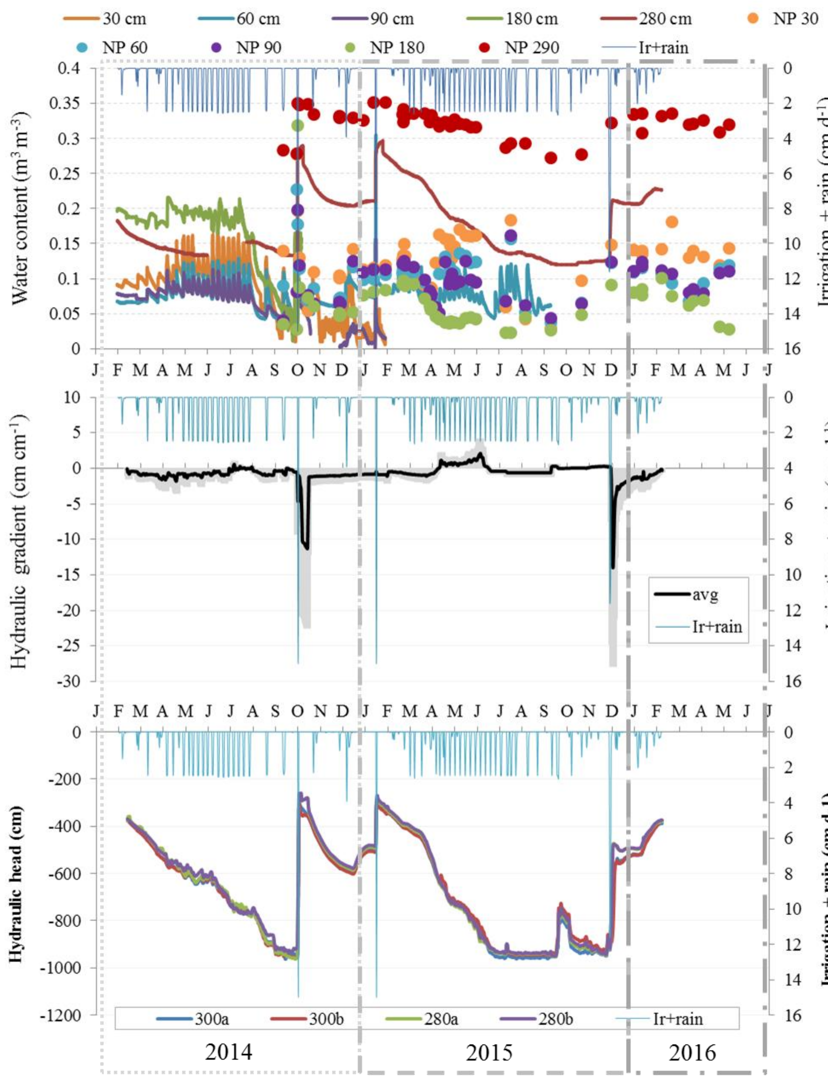

Figure 5. *Changes over time in volumetric soil moisture content (C, θv) over the entire rooting zone gathered using 5TE sensors and neutron probe (NP) (upper panel) in average hydraulic gradient between 300 and 280 cm (middle panel) and in daily hydraulic head at 280 and 300 cm below land surface (lower panel).*

1. *Mass balance* – In the mass balance method, the annual N mass lost through leaching (*M*), was calculated using the equation:

$$M = \sum_{i=1}^{12} V_i C_i \qquad (2)$$

where *V* is the volume of water leaching every month (*i*) below 3 m soil depth (m^3), *C* is the average N concentration in the leaching water at that depth during that month ($g\ m^{-3}$). The volume of water leaching below 3 m soil depth was calculated for each site using:

$$L = (Ir + rain) - (ET_c) - (\Delta S) \quad (3)$$

$$V = LA \quad (4)$$

where L is the weekly water leaching flux (cm week^{-1}), *Ir* and *rain* are the cumulative weekly irrigation and precipitation, respectively (cm week^{-1}), ET_c is the cumulative weekly water loss through evapotranspiration (cm week^{-1}), ΔS is the change in soil water storage over a week (cm week^{-1}) and A is a hectare (10,000 m^2). ΔS was calculated both based on 5TE data and NP data (Figure 6). In the 5TE based storage calculations the lithological profile was accounted for. ET_c was estimated based on ET_o data from California Irrigation Management Information System – Station No.188 (CIMIS 2014), which was multiplied by crop coefficients (K_c) based on the work of Goldhamer (2012).

2. *Darcy Method* – In this method, the leaching flux below a depth of 3 m was calculated daily using the empiric law of Darcy (Figure 6):

$$q = K\frac{\partial h}{\partial z} \quad (5)$$

where q is the leaching flux (cm d^{-1}), K is the hydraulic conductivity (cm d^{-1}), h is the total hydraulic head (cm) and z is the elevation above a vertical datum (cm). The hydraulic conductivity was calculated daily as a function of the matric potential ($K(\psi)$) using the van Genuchten (1980) Mualem (1976) formula:

$$K(\psi) = K_s\left(\frac{1}{\left[1+(\alpha|\psi|)^n\right]^{1-\frac{1}{n}}}\right)^{\frac{1}{2}}\left[1-\left(1-\left(\frac{1}{\left[1+(\alpha|\psi|)^n\right]^{1-\frac{1}{n}}}\right)^{\frac{n}{n-1}}\right)^{1-\frac{1}{n}}\right]^2 \quad (6)$$

where K_s is the hydraulic conductivity at saturation (cm d^{-1}), ψ is the matric potential (cm) and □ (cm^{-1}) and n (–) are empirical parameters which are related to the inverse of the air entry pressure and the pore-size distribution, respectively. The field gathered matric potentials at depths of 2.8 and 3.0 m data and the water content at depth of 2.9 (5TE and the NP), were used to generate eight in-situ retention curves for each monitoring site and RETC code (van Genuchten et al., 1991) was used to fit the □ and n parameters for each curve to get the daily $K(\psi)$ (Eq. 5) (Figure 7, Sites A-H). K_s of the soils at depth of 2.8 m in each site were estimated using the permeameter method. K_s was calculated using (U.S. BR-DO-MEB, 1990):

$$K_s = \frac{Q}{2\pi h^2}\left\{\ln\left[\frac{h}{r}+\sqrt{\left(\frac{h}{r}\right)^2+1}\right]-\left[\frac{\sqrt{\left(\frac{h}{r}\right)^2+1}}{\frac{h}{r}}\right]+\frac{1}{\frac{h}{r}}\right\} \quad (7)$$

where Q is steady flow rate (ml s^{-1}), h is height of constant water head in the borehole (cm), r is borehole radius (cm) and π is 3.14. Similar to the mass balance method, nitrogen leaching below the root zone was calculated daily using equations 1 and 3, where L was substituted by q (Figure 6).

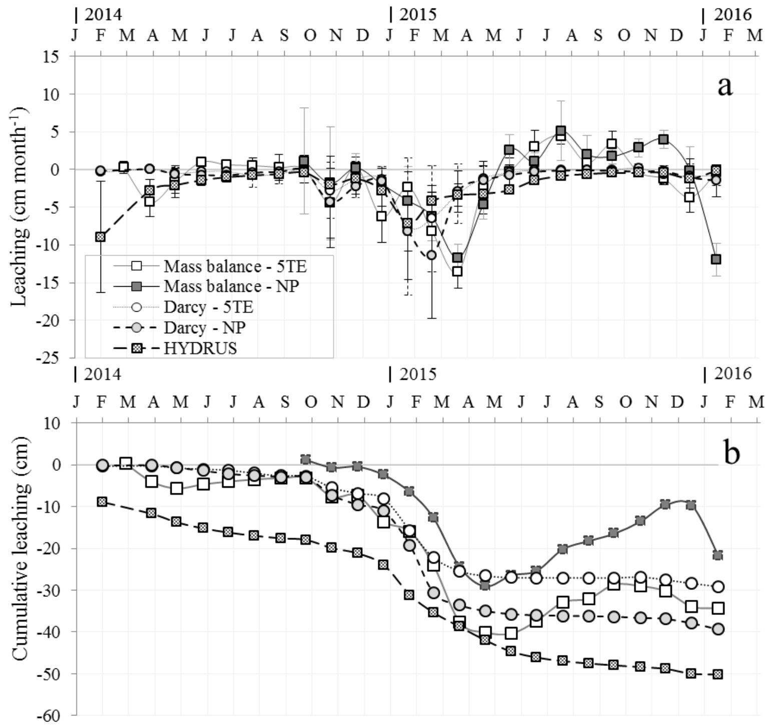

Figure 6: *Average monthly leaching flux (a) and cumulative flux (b) at soil depth of 3 m calculated based on in-situ vadose zone data using mass balance, Darcy flow equation and HYDRUS modeling.5TE indicates TDR volumetric water content as model utilized data basis, and NP indicates data from neutron probe.*

3. *Inverse Modeling Framework Methodology* – The HYDRUS code (Šimůnek et al., 1998) along with MATLAB software (MathWorks, 2012) were used as an inverse modeling framework to estimate water leaching and NO_3^- transport at a soil depth of 3 m. In the inverse modeling, field gathered data of soil water content, soil matric potential, and their temporal changes was used as observation points. The field gathered data was first used in an optimization program that combined the Genetic Algorithm (GA) global optimizer and the FMinSearch and FMinCon local optimizers (available in MATLAB) (for more information on the optimizer see Coleman and Li (1996), Lagarias et al. (1998) and Whitley (1994)). In the optimization process the program incorporated effective hydraulic properties to soil horizonation. The optimization process used an initial population of parameter sets (‘P’) which was randomly picked from a defined and bounded parametric space (Table 2). Once the initial parameters were picked (i.e. four parameters of van Genuchten (1980) equation: water content at saturation – θs, α, n and Ks, assuming m = 1-1/n.), the Richards’ flow equation (Richards, 1931) was solved in HYDRUS coupled with Feddes et al. (1978) root water uptake model (using: h2 = –600 cm, h3 = –8000 cm and ωc = 0.3) and Vrugt et al. (2001) one-dimensional root distribution model (z* = –10 cm, z0 = –145 cm and pz = 0 (linear)) models.

Table 2: Parametric space limits used in the optimization

Parameter	Min-limit	Max-limit
θr (cm cm^{-1})	0.0	0.2
θs (cm cm^{-1})	0.2	0.34
log_{10}(□)(cm^{-1})	-3	-1
n (-)	1.15	3.10
log_{10}(□s) (cm d^{-1})	-0.5	2.5

For each tested parameter set, differences between simulated and measured observations were quantified with a second-order moment of residuals, which gives more weight to large errors in the objective function (i.e. squared errors). Those residuals were then averaged; uniform weights were attributed to different observations of the same type for local water content, total water storage and matric potential. Temporal changes of water content and storage were considered as separate observations, which were attributed weights proportional to their amplitude (i.e. large changes have more weight). Average water status was used to normalize the average residuals. The normalization enabled to aggregate the different error types, with no effect of their units, into a single non-dimensional value. The aggregated value was than stored, and a new set of parameters P was picked from the parametric space, using either global or local optimizer. The optimizers kept on looking for new P values in the parametric space until the aggregated value of the objective function reached the minimal value (i.e. best fit). Local optimizers were run after the global optimizer to refine the solution locally. In the optimization process, the residuals were calculated in a time frame of 8 – 12 months out of the 24 months of data. Extra observations were used for validation of the optimized parameters.

In all the simulations the top boundary conditions of precipitation and irrigation were based on field measurements, while evapotranspiration was defined based on ET_o data from CIMIS combined with *Kc* parameters of Goldhamer (2012) to transition linearly from the low plateau (*Kc1*) to the high plateau (*Kc2*), yearly. The monitored matric potentials and water contents were used to generate the initial soil matric potential profile. Initial matric potentials in-between observation depths were linearly interpolated. In the modeling, the continuous in-situ water content measurements of the 5TE sensors at each site were linearly correlated to the NP measurements from the corresponding depth at each site. The correlation factor for each site ($R^2 > 0.75$) was then used to convert the 5TE measurements to continuous NP water content measurements.

Darcy flux calculations showed that the yearly average fluxes below 3 m soil depth at the orchard sites, based on 5TE data and on NP data, were fairly similar (2014: 12.0 vs. 14.9 cm y^{-1}, respectively; 2015: 12.6 vs. 18.7 cm y^{-1}, respectively). In all growing seasons the water flux across the orchard remained in the same range (1 – 33 cm y^{-1}). However, up to 3 fold differences were observed between the flux calculated at each site based on 5TE and NP data. Similar to the Darcy method, the yearly average fluxes calculated based on the mass balance approach (Eq. 2) and NP and 5TE data were comparable (18.3 vs. 15.1 cm y^{-1}). Moreover, same differences (up to 3 fold) were observed between the fluxes calculated based on 5TE and NP data at each sites. In both methods, big differences were observed between the 5TE and NP based fluxes at Site-E (15 – 20 vs. 0.35 – 1.0 cm y^{-1}, respectively). The differences between the 5TE and NP base calculations are an outcome of the differences between the readings of the two methods, which results from two major factors: (i) soil volume measured by the sensor and, (ii) installation procedure. The soil volume measured by the 5TE sensor (0.0007 m^3; Decagon-Devices, 2016) is 20 – 700 times smaller than the volume measured by the NP (0.014 to 0.5 m^3; Robinson et al., 2008). In addition to the much smaller volume measured by the 5TE sensor, it is difficult and sometimes impossible to properly install it at depth of 2.9 m (i.e. push the whole length of its semi-flexible brittle prongs into undisturbed sediment at the side wall of a borehole). It is therefore more reasonable to assume that NP readings, which sample a much larger area of undisturbed soil profile, are more representative of the 'true' water distribution in the subsurface, especially in deep vadose zone, as suggested by Yao et al. (2004). However, at an orchard scale the need for an operator and relatively slow data acquisition process makes it very hard to use NP as a tool to study the temporal dynamics (minutes to hours) of water along the vadose zone, especially over long periods; data that is easily acquired by sensors such as the 5TE when connected to data loggers.

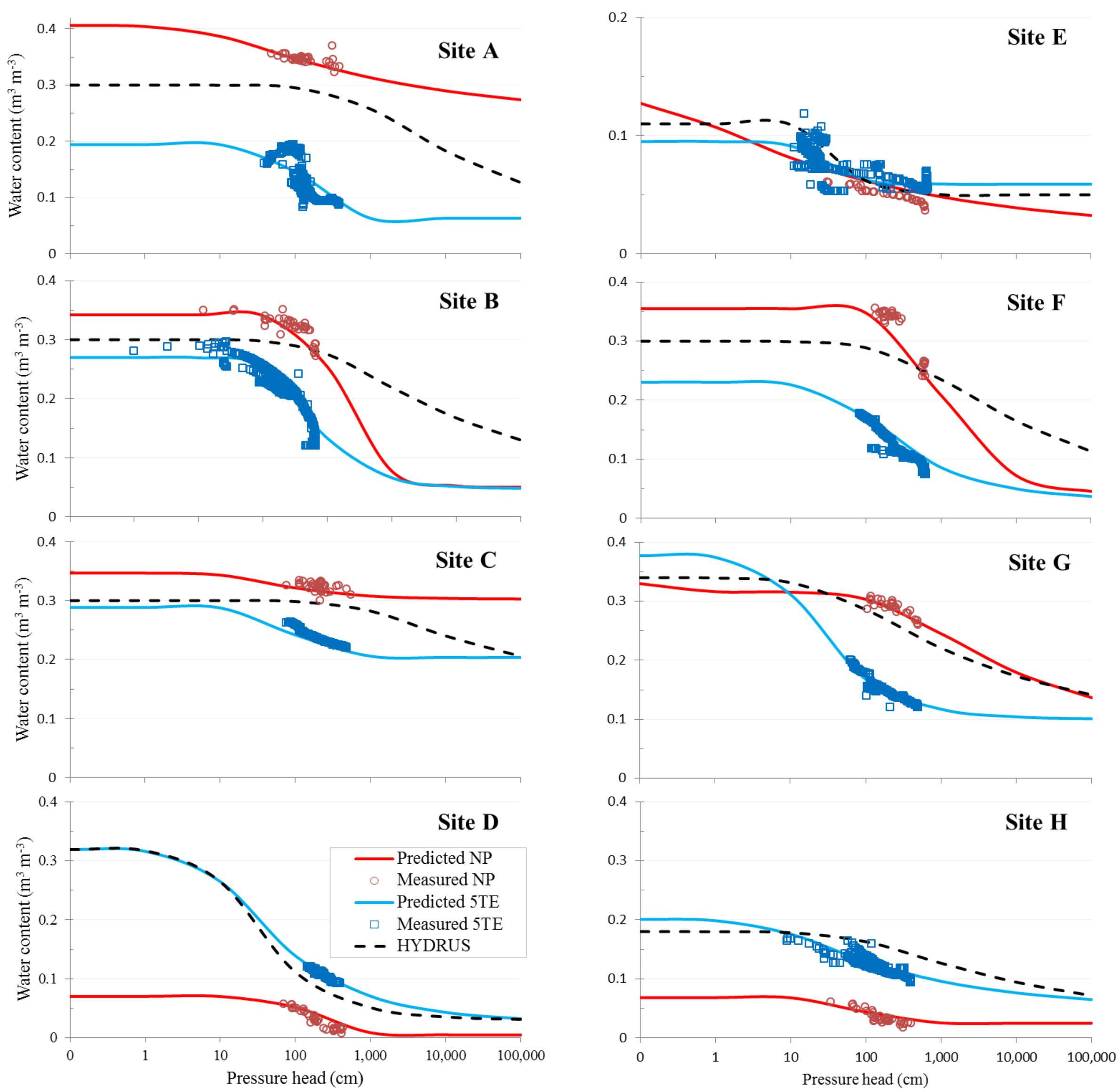

***Figure 7**. Retention curves for the soils at depth of 2.8 – 3.0 m based on 5TE, NP and tensiometer data from the eight vadose zone monitoring sites.*

The monthly water fluxes calculated by the model were in good agreement with the fluxes calculated by the other methods (Figure 8a). Nonetheless, through most of the year the orchard average monthly flux calculated by the model was slightly higher than the flux calculated by the other methods, resulting higher cumulative flux (Figure 8b). Similar to the other methods, very high fluxes were observed in Site E during the 2014 and 2015 growing seasons (56 and 30 cm y^{-1}, respectively). The range of fluxes calculated by the model for the different sites was smaller than the range in the other methods (2014: 22 – 30 cm y^{-1}, excluding Site E; 2015: 15 – 36 cm y^{-1}).

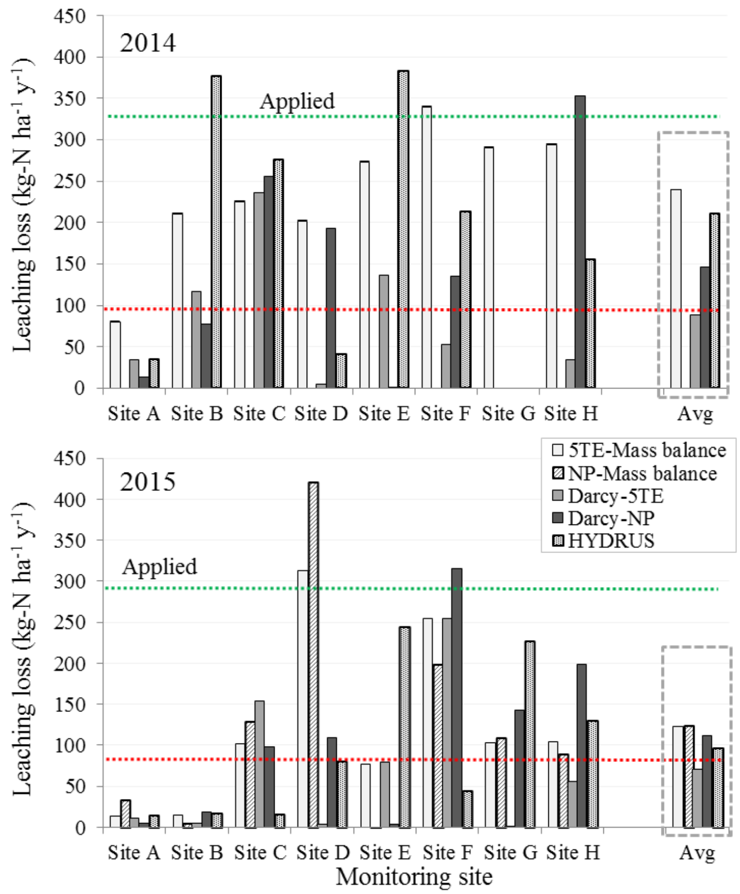

Figure 8: *Yearly NO_3^--N leaching losses below soil depth of 3 m under the monitored sites and the orchard average for the three different methods (mass balance, Darcy flow and HYDRUS inverse modeling). Upper and lower dotted lines in each panel represent the N-load applied and the annual N accumulation, respectively.*

G. Discussion and Conclusions:

During all of the seasons for these experiments, yields for the AGP, P&F and HFLC treatments were not statistically significantly different (Figure 2) and were all in an economically sustainable range of from approximately 2,600 to 3,200 lb.-kernel per acre.

From initiation of the experiment to date monitoring has produced more than 1300 pore-water samples collected from the soil profile under all orchards. From January 2014 through June 30 2016, 150 pore-water samples were collected. Similar to previous years, high spatial variability was still evident in N concentrations within the orchard. Across all treatments during the 2014, 2015 and 2016 seasons, NO_3^- concentrations ranged from lower than the drinking water standard (<10 mg-NO_3^--N L^{-1}) up to more than ten times the drinking water standard (Figure 3). Comparison between the temporal variability observed in the pore-water N concentration and the soil extraction support our previous conclusions that despite the deep wetting following the flood irrigation, a significant immobile N pool remains and dominates the total N storage at 1.5 – 3.0 m soil depth (Baram et al., 2016; Smart et al., 2015).

In all of our calculations the yearly mean NO_3^- concentration at each one of the monitoring sites was used. Over the orchard the coefficient of variation of NO_3^- concentration increased with distance between sites, up to a distance of 80 m where it remained at a value of ~100% (Figure 4a). On the local scale (up to 70 m between sites), a similar trend of increased variance with distance was observed on one row (Site A), while on another row no trend was observed (Site B) and on a third row (Sites C) opposite trend was observed (Figure 4b). Both statistical methods, along with the methods previously reported (Smart et al., 2015), suggested that additional parameters not considered in this study, such as water application non-uniformity at the tree scale and sampling location relative to the emitters (Rolston et al., 1991), as well as spatial variations in root nutrient and water uptake rates within and between trees (Couvreur et al., 2016). Variation in yield and N content in the kernels (Siddiqui and Brown, 2013; Silva et al., 2013) was evident.

All three methods (i.e. mass balance, Darcy-flux and HYDRUS modeling) indicated high downward fluxes during the winter end early spring (December through late April), especially following flood irrigation events. Latter in the season (May through October) the soil profile dried and the downward flux approached zero (less negative) and even became positive, indicating upward water flux (Figure 6a). In 2014 the calculated average cumulative flux greatly varied between the three methods (12 – 32 cm y^{-1}), while in 2015 all the methods indicated more similar fluxes (12 – 22 cm y^{-1}) (Figure 6b). We believe that the upward flow fluxes calculated in the mass balance approach are inaccurate, due to the dry conditions which prevailed in the subsurface from May through October (ψ < -150 cm) and the corresponding calculated low hydraulic conductivities ($K(\psi)$ < 0.001 cm d^{-1}). Non-uniformity in the wetting patterns of the micro-sprinklers in the field (most of the water falls 1.8 – 2.4 m away from the sprinkler, field observations) generates conditions in which only part of the infiltrating irrigation water is captured by water content sensors. Accordingly, as the soil profile dries the difference between the applied water and the observed change in storage (ΔS) increases. In order to sustain the mass balance, water needs to enter the upper soil profile (< 3 m) from its bottom boundary (> 3 m) as upward water flux (Eq. 2). Differences between the orchard average ET_c values (Et_0 x Kc) and the actual ET value at the monitored trees are another driver for the unrealistic upward flow values. This assumption is strengthen by the work of Couvreur et al. (2016) that showed 5–8% spatial variations in root water uptake rates within and between trees in an almond orchard.

Darcy flux calculations showed that the yearly average fluxes below 3 m soil depth at the orchard sites, based on 5TE data and on NP data, were fairly similar (2014: 12.0 vs. 14.9 cm y^{-1}, respectively; 2015: 12.6 vs. 18.7 cm y^{-1}, respectively). In all growing seasons the water flux across the orchard remained in the same range (1 – 33 cm y^{-1}). However, up to 3 fold differences were observed between the flux calculated at each site based on 5TE and NP data. Similar to the Darcy method, the yearly average fluxes calculated based on the mass balance approach (Eq. 2) and NP and 5TE data were comparable (18.3 vs. 15.1 cm y^{-1}). Moreover, same differences (up to 3 fold) were observed between the fluxes calculated based on 5TE and NP data at each sites. In both methods, big differences were observed between the 5TE and NP based fluxes at Site-E (15 – 20 vs. 0.35 – 1.0 cm y^{-1}, respectively). The differences between the 5TE and NP base calculations are an outcome of the differences between the readings of the two methods, which results from two major factors: (i) soil volume measured by the sensor and, (ii) installation procedure. The soil volume measured by the 5TE sensor (0.0007 m^3; Decagon-Devices, 2016) is 20 – 700 times smaller than the volume measured by the NP (0.014 to 0.5 m^3; Robinson et al., 2008). In addition to the much smaller volume measured by the 5TE sensor, it is difficult and sometimes impossible to properly install it at depth of 2.9 m (i.e. push the whole length of its semi-flexible brittle prongs into undisturbed sediment at the side wall of a borehole). It is therefore more reasonable to assume that NP readings, which sample a much larger area of undisturbed soil profile, are more representative of the ‘true’ water distribution in the subsurface, especially in deep vadose zone, as suggested by Yao et al. (2004). However, at an orchard scale the need for an operator and relatively slow data acquisition process makes it very hard to use NP as a tool to study the temporal dynamics (minutes to hours) of water along the vadose zone, especially over long periods; data that is easily acquired by sensors such as the 5TE when connected analog to digital converting data logging devices.

Darcy flux calculations showed that the yearly average fluxes below 3 m soil depth at the orchard sites, based on 5TE data and on NP data, were fairly similar (2014: 12.0 vs. 14.9 cm y^{-1}, respectively; 2015: 12.6 vs. 18.7 cm y^{-1}, respectively). In all growing seasons the water flux across the orchard remained in the same range (1 – 33 cm y^{-1}). However, up to 3 fold differences were observed between the flux calculated at each site based on 5TE and NP data. Similar to the Darcy method, the yearly average fluxes calculated based on the mass balance approach (Eq. 2) and NP and 5TE data were comparable (18.3 vs. 15.1 cm y^{-1}). Moreover, same differences (up to 3 fold) were observed between the fluxes calculated based on 5TE and NP data at each sites. In both methods, big differences were observed between the 5TE and NP based fluxes at Site-E (15 – 20 vs. 0.35 – 1.0 cm y^{-1}, respectively). The differences between the 5TE and NP base calculations are an outcome of the differences between the readings of the two methods, which results from two major factors: (i) soil volume measured by the sensor and, (ii) installation procedure. The soil volume measured by the 5TE sensor (0.0007 m^3; Decagon-Devices, 2016) is 20 – 700 times smaller than the volume measured by the NP (0.014 to 0.5 m^3; Robinson et al., 2008). In addition to the much smaller volume measured by the 5TE sensor, it is difficult and sometimes impossible to properly install it at depth of 2.9 m (i.e. push the whole length of its semi-flexible brittle prongs into undisturbed sediment at the side wall of a borehole). It is therefore more reasonable to assume that NP readings, which sample a much larger area of undisturbed soil profile, are more representative of the ‘true’ water distribution in the subsurface, especially in deep vadose zone, as suggested by Yao et al. (2004). However, at an orchard scale the need for an operator and relatively slow data acquisition process makes it very hard to use NP as a tool to study the temporal dynamics (minutes to hours) of water along the vadose zone, especially over long periods; data that is easily acquired by sensors such as the 5TE when connected to data loggers.

The main limitation to the Darcy flux estimates came from its independence from mass balance conservation constraints. Accordingly, in three out of the eight monitoring sites, the field measured saturated hydraulic conductivities (K_s) had to be lowered by up to two orders of magnitude, in order to make sure that the drained flux did not exceed the applied water (especially following flood irrigation events). In all cases the corrected K_s values were in the range expected for the specific soil type (Clapp and Hornberger, 1978). One exception to that trend was observed in the K_s value for the 5TE measurements at Site E, where K_s value was lower by at least one order of magnitude than the expected value. We believe that this deviation is a result of the installation procedure of the 5TE sensor at that site, where fine sediment fell down into the borehole during the installation, and increased the water content values compared to undisturbed sediment.Overall the generation of in-situ retention curve, and its applicability in calculating the leaching flux based on monitoring of the hydraulic conditions in the vadose zone (matric potential and/or water content) is very accurate and is not biased by the uncertainty associated with tree scale ET assessments. However, care must be taken to make sure that the leaching values are constrained by mass balance conservation.

The monthly water fluxes calculated by the model were in good agreement with the fluxes calculated by the other methods (Figure 8a). Nonetheless, through most of the year the orchard average monthly flux calculate by the model was slightly higher than the flux calculated by the other methods, resulting higher cumulative flux (Figure 8b). Similar to the other methods, very high fluxes were observed in Site E during the 2014 and 2015 growing seasons (56 and 30 cm y^{-1}, respectively). The range of fluxes calculated by the model for the different sites was smaller than the range in the other methods (2014: 22 – 30 cm y^{-1}, excluding Site E; 2015: 15 – 36 cm y^{-1}).

Unlike the two aforementioned methods, the HYDRUS modeling approach taken by us was constrained by both mass balance and hydraulic properties of the soil profile. Distinct to the Darcy method, where the hydraulic properties of the soil layer at depth of 2.8 – 3.0 m were characterized, the model optimization process fitted the field gathered data to get the hydraulic properties of two general soil layers of high and low permeability. In most cases the retention curves from the HYDRUS model fitted parameters were less steep than the RETC predicted ones, indicating higher leaching potential at the low matric potentials for the model (Figure 6). The good agreement between the annual water losses, calculated based on the HYDRUS model and the Darcy method, suggests that the use simple root water uptake model (Feddes et al., 1978) and one-dimensional root distribution model (Vrugt et al., 2001) in addition to the Richards' flow equation was sufficient to capture the water flow dynamics at the different sites.

The orchard average NO_3^- fluxes below the effective root zone, across measuring and calculation methods were all in the same order of magnitude (80 – 240 kg-N ha^{-1} y^{-1}). In most sites Darcy flux calculations with 5TE data had the lowest NO_3^- fluxes, while mass balance calculations had the highest flux (Figure 8). In both growing seasons, no correlation was observed between the water flux at depth of 2.9 m and the mobile pore-water NO_3^- concentration at that depth ($R^2 = 0.017$); that is: sites with high water flux did not have low pore-water NO_3^- concentration, or vice versa. Based on the work of Baram and colleagues (2016) which showed that the N load in the soil at that research site did not change significantly between the two growing seasons, the orchard average annual N accumulation (applied – removed) served as good reference for the maximal load available annually for leaching. Nonetheless, the differences in N removal at the tree/row scale, suggest high spatial variability in N-accumulation within the orchard. The work of Silva et al. (2013) which studied multiple almond orchards for four years, shows similar variability in yield and N contents. This spatial variability may explain the high spatial variability in pore-water NO_3^- concentration at a depth of 2.9 m (Figure. 3) and the differences between the annual N losses at the different monitoring sites (Figure 8).

The good agreement between the annual N accumulation and the vadose zone based estimates of N losses below the effective root zone indicated that at this research site, eight vadose zone monitoring sites, representing different soil layering, were sufficient to capture the spatial variability in N losses at the orchard scale. The conserved research site represents orchard management in which pre bloom fill of the soil water storage leads to leaching mainly early in the growing season when the soil profile is wet (February through early May). This management practice prevents long term N buildup in the subsurface, and also leads to increased N losses during early season fertilizer applications (Baram et al., 2016). In orchard where minimal leaching occurs, N would probably buildup in the subsurface, similar to the natural buildup of N in arid/semiarid regions (Stone and Edmunds, 2014). Accordingly, at such sites pore-water sampling below the effective root zone may not represent the annual N-buildup, as observed under the pistachio orchard. Based on the spatial variability of the soil layering at the orchard scale, it is hard to determine whether eight vadose zone monitoring sites would be stuffiest to capture the spatial variability in N and water losses under different orchards. Indication to the limitation of predetermined number of soil sampling sites to represent mean field NO_3^- content was presented by Ilsemann et al. (2001).

Although the annual N losses can be estimated based on mass balance and vadose zone data, our results also indicated that it is harder to estimate the orchard average NO_3^- concentration in the pore-water leaching below the effective root zone. Using simple mass balance of N and water [(N-applied – N-removed)/(Rain + irrigation – ET_c)] indicated that the NO_3^--N concentrations in the leaching water should have been 38 and 143 mg L^{-1}, for the 2014 and 2015 growing seasons, respectively. At the same time, when annual N accumulation, was divided by the annual leaching estimated by water mass balance (Eq. 2), Darcy method (Eq. 4) and HYDRUS modeling, NO_3^--N concentrations in the leaching water should have been in the range of 82-43 and 66-45 mg L^{-1}, respectively. These NO_3^--N concentrations are lower than the orchard average concentration based on pore-water sampling (109 and 75 mg L^{-1}, respectively). The big difference between calculated orchard average pore-water NO_3^--N concentrations and the concentration in the sampled pore-water probably stems from spatial variability in N uptake under uniform N applications along with the dominance of preferential flow and N-transport at the orchard scale (Baram et al., 2016; Onsoy et al., 2005; Russo et al., 2014). Identification and quantification of high/low productivity zones within an orchard may be used to improve N losses estimates, as previously suggested by Delgado and coworkers (2005) for irrigated corn fields.

Conclusions

- Yields and potential yields did not differ among the treatments of HFLC, AGP and P&F thus verifying that for nut crops a unit of N via assimilation of NH_4^+-N and NO_3^--N from dilute solutions is a viable management practice in terms of economically sustainable production.
- Within orchard variability in soil water NO_3^- was widespread and has potentially indicated that root zone monitoring of soil water NO_3^- levels will not likely present a viable solution for practitioners to undertake self-assessment exercise
- Modeling exercises indicated that more complex approaches of *ca* Darcy equation and HYDRUS inverse modeling produced no more accurate results than the mass balance approach alone. This is an extremely important finding in as much as it suggests practitioners can carry out mass balance exercises (N-applied – N-removed) in order to have a self-assessment tool for N-loss to NO_3^- leaching.

G. Project Impacts:

The project has had widespread impact for advancing the environmentally safe and agronomically sound use of fertilizing material, in particular nitrogen. It has made a major contribution by presenting materials to several thousand practitioners at grower sponsored venues. It has provided innovation by the realization of the use of computer technologies to control fertigation timing, duration and amounts of material (N) delivered and whether or not such material is injected at the beginning or end of a fertigation event. Furthermore, the Central Valley Water Board is using our data to 'ground verify' various aspects of their N management plan worksheet. Our data is used to update the Almond Nitrogen Model for BMPs information on mobilization of reactive N (NO_3^- and N_2O) which numerous practitioners use. Thus, many changes in practice/behavior are coming about as a consequence of the results of this project.

I. Outreach Activities Summary:

Task 14 – Present the first results and experimental principles and project goals at grower and other stakeholder meetings.

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

MW Wolff, 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.

W Salas, 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.

DR Smart (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.

DR Smart (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.

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.

DR Smart, 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.

DR Smart (2015) "How N Leaky are Vineyards and Nut Crop Orchards?" US:New Zealand Science Workshop – Water Utilization and Nutrient Management in Perennial Horticulture, Oct 20-23, 2015 UC Davis, California, 40 attendees.

DR Smart **"**Optimizing the Use of Groundwater Nitrogen for Nut Crops." Western Plant Health Association/CDFA

Task 15 – In collaboration with Almond Board and Pistachio Research Committee and Farm Advisors from relevant districts, organize 2 or more “field days” to present the new findings to growers, explain how to use the developed models for nutrient decision, illustrate and demonstrate P&F approach, and present preliminary outcomes.

Not carried out as a consequence of limited field space and concerns of the grower cooperators.

Task 16 – Coordinate web and paper publications in grower and peer reviewed journals. Prepare technical summary for use by commodity boards, water boards and other agencies.

DR Smart (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.

DR Smart, 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.

Baram, S., Couvreur, V., Harter, T., Read, M., Brown, P.H., Hopmans, J.W., Smart, D.R., 2016. Assessment of orchard N losses to groundwater with a vadose zone monitoring network. Agric. Water Manag. 172, 83–95. doi:10.1016/j.agwat.2016.04.012

Couvreur, V., Kandelous, M.M., Sanden, B.L., Lampinen, B.D., Hopmans, J.W., 2016. Downscaling transpiration rate from field to tree scale. Agric. For. Meteorol. 221, 71–77. doi:10.1016/j.agrformet.2016.02.008

Baram, S, V Couvreur, T Harter, M Read, PH Brown, M Kandelous, **DR Smart**, and JW Hopmans (2016) Estimating Nitrate Leaching to Groundwater from Orchards: Comparing Crop Nitrogen Excess, Deep Vadose Zone Data Driven Estimates and HYDRUS Modeling. *Vadose Zone Journal*, 15:11-24.

J. Factsheet/Database:

10. Findings (Discuss results and conclusions, including advice and resulting practice meth ods)

1. Project Title: Optimizing the Use of Groundwater Nitrogen for Nut Crops.
2. Grant Agreement Number: FREP Grant No:12-0454-SA
3. Project Leaders: Project PI: David R. Smart, Professor, Department of Viticulture and Enology, UC Davis. Project Co-PIs: Thomas Harter, Specialist, Department of Land, Air & Water Resources UC Davis, Patrick Brown, Professor, Department of Plant Sciences UC Davis. Jan Hopmans, Department of Land, Air & Water Resources UC Davis.
4. Start Year/End Year: October 1, 2012 to December 31, 2016.
5. Madera (an almond and a pistachio orchard), Turlock (an almond orchard)
6. Stanislaus and Madera counties.
7. Highlights:
   - Project discovered no differences in yield between Advanced Grower Practice (Almond Nitrogen Model). University of California, One Shields Avenue, Davis CA 95616. URL http://ucce.ucdavis.edu/rics/fnric2/almondNKmodel/almond_model.html, 2014) high frequency low nitrogen concntration (spoonfeed) and pump and fertilize N management proactices.
   - Project discovered extreme variation in soil solution NO_3^- , thus answering a major question concerning whether or not lysimeters are a feasible means of self-assessment for growers. They are not.
   - Project found no substantial differences in estimating NO_3^- leaching rates as estimated using advanced models and a simple mass balance approach. The significance of this finding is that growers can easily use the mass balance approach to estimate their individual nitrogen use efficiency with respect to NO_3^- leaching.
8. Introduction:

   The proposal tested two easily adaptable practices of fertilizing micro-irrigated nut crops with N to diminish reactive N mobilization (NH_3, NH_4^+, N_2O, NO_x and NO_3^-) and contrast the two previous treatments with P&F N management. The two other treatments consisted of 4 to 6 split applications of 40 to 60 units of N according to the Almond Nitrogen Model and referred heretofore as Advanced Grower Practice (AGP) and High Frequency Low N Concentration nitrogen provision (HFLC, spoonfeed). Reactive N forms have several environmental consequences including ground water NO_3^- contamination. Fundamental basis of this proposal was to bring together a multi-disciplinary team of scientists to intensively monitor a suite of California nut crops under P&F N management. The problem of mobilization of reactive nitrogen into air and water is currently one of the most important subject areas with respect to environmental sustainability for California agriculture and multi-disciplinary approaches will be needed to help resolve this problem. Nitrate (NO_3^-) is the primary contaminant of well waters and is extensively found in tapped aquifers in California's Central Valley (Viers et al. 2012). Nitrate contamination of water is reported to be "overwhelmingly the result of … agriculture activities" (Viers et al. 2012) and particularly application of synthetic N fertilizers to crops. The problem addressed in this proposal was whether or not P&F (eg. Viers et al. 2012, Table 9 p. 70) was a feasible mitigation option for growers of California's N intensive nut crops and other perennial tree crops, which currently represent well over 30% of California's irrigated lands (Smart et al. 2011) while maintaining sustainable yields.

9. Methods/Management: We established completely replicated fertigation regimes that used an AGP treatment using grower on-site equipment and provided monitoring of leaf and fruit N status during the season. The P&F regime accounted for the concentration of groundwater NH_4^+ and NO_3^-. For HFLC dositrons were utilized to accomplish high frequency fertilization.

   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). Installed sensors monitor processes mainly below the root zone (Figure 9).

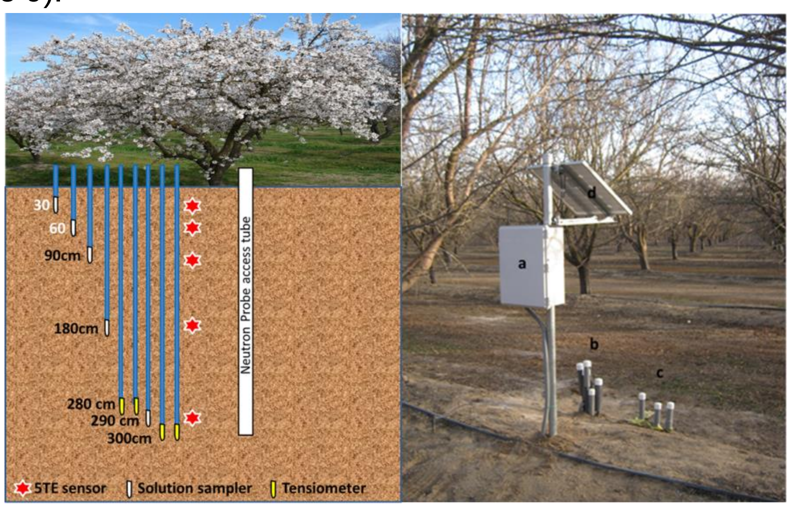

Figure 9: *The basic set-up of the intensively monitored trees (left panel), and the way it appears in the almond orchard within the Madera HVA orchard (right panel), electronics enclosure (a), lysimeters (b), tensiometers (c).*

10. Findings: A number of findings were realized that update the thinking and advance the science within the project framework: 1) One major finding was that yields did not differ between the AGP, HFLC and P&F treatments, thus highlighting that P&F is a viable alternative. 2) A second major finding was extreme variability in soil solution NO_3^- concentration, thus rendering as infeasible lysimeters as a potential self-assessment approach. 3) A third major finding was equivalency between more advanced modeling approaches versus mass balance (N-applied – N-removed) as a means of growers undertaking self-assessment exercises. What this means is that growers will have an easily calculable manner of undertaking self-assessment. 4) A fourth major finding was the observation that from average NO_3^- fluxes below the effective root zone, across all measuring and calculation methods, were all in the same order of magnitude of from 80

to 240 kg-N ha^{-1} y^{-1}. These data suggest there is vast room for improvement of grower practices, albeit will be up to grower assistance organizations like CDFA FREP and the commodity boards to fund research related to the above as well as disseminating researcher findings.

The HFLC treatment in order to be successfully carried out at the field scale will likely move forward using computerized control systems *eg*. http://www.phtechllc.com/products/fertigation while technical equipment used for P&F and AGP already exist and in many cases involve simple calculations in conjunction with using pre-existing fertigation equipment.

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