A. Project Information:

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Project title: Irrigation and Nitrogen Management, Monitoring, and Assessment to Improve Nut Production While Minimizing Nitrate Leaching to Groundwater

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B. Abstract:

This project provides a comprehensive assessment of groundwater nitrate impact from a promising best management practice, High Frequency Low Concentration fertigation (HFLC). The project evaluates HFLC and compares three monitoring approaches to assess nitrate impact to groundwater: (1) Groundwater monitoring, the regulatory gold standard to assess pollution sources. Groundwater sampling is performed at 20 monitoring wells (screened at 7-14 m below ground surface). (2) Vadose zone monitoring provides early feedback on potential groundwater nitrate discharge but can be labor-intensive. Vadose zone monitoring is performed at 7 multi-level sites (0-3m depth) where soil moisture, nitrate, and ammonium fluxes are measured. (3) The NUE or nitrogen balance is a tool familiar to growers under the ILRP but its relationship to actual groundwater nitrate discharge is not well understood. Field monitoring data are collected to calculate water and nitrate (N) mass balance, as employed by the ILRP and enhanced with on-site measurement equipment (flow-meter, ET-station). The study makes important findings for growers, for consultants, and for regulatory agencies and the public:

Key Results for Growers: HFLC has shown promising results during the seven-year span of this project (2018-2024). On average, reported NUE has increased by 18% and kernel yields have increased by 15% when compared to the previous five years of pre-HFLC orchard management. Residual N mass in the first 60 cm of the orchard soils and pore-water nitrate concentrations in the vadose zone (measured to a depth of 280 cm) have both shown decreases following the switch to more efficient nutrient management.

Key Results to Environmental Consultants: Numerical models suggest that although nitrate concentrations quickly decrease in the shallow vadose zone, there will be an up to 30-year delay between the start of HFLC and an observable decrease in groundwater nitrate concentrations at this site. This delay is caused by the long transport time that nitrogen experiences between surface application and recharge at the water table, as well as slow movement of groundwater flow. Our unsaturated zone models suggest that this transport time can be between 5 and 15 years, depending on soil types (i.e. water

and nitrate-N move slower in clayey soils than in sandy ones). Computer simulations of the orchard's vadose zone and groundwater, calibrated to our extensive data set, suggest that lower irrigation- and nitrogen-efficient young orchard management may be the largest contributor to the highly spatially distributed groundwater N concentrations measured in the monitoring wells and throughout the vadose zone soils. Other causes of the large variability in groundwater nitrate may stem from block-scale non-uniformity of fertilizer and irrigation application, but less so from the highly heterogenous local geology. Calibration of the computer simulation models was most aided by vadose zone water content measurements to 10 ft, which was key to properly determine the amount of recharge and, hence, the proper dilution of residual nitrate mass in the leachate to measured concentrations in the vadose zone and in groundwater (legacy leaching). Properly determining recharge rates also reduces the uncertainty about travel time in the deep vadose zone and affects groundwater flow.

Key Results to Regulatory Agencies and the Public: Importantly, with respect to groundwater quality control, monitoring and assessment, this study makes the following key findings: First, nitrate concentrations in first-encountered groundwater across an orchard farm are highly variable, ranging over an order of magnitude, which has implications for the design and proper application of groundwater monitoring networks. Second, spatially averaged nitrate concentration across the farm (orchard), at first encountered groundwater, are consistent with the NUE, i.e., with field/orchard/farm scale nitrate losses estimated from N mass balance, with proper recharge estimates. And, third, nitrate transport in the unsaturated zone, under efficient irrigation management, in California climates, and/or in drought years with regularly less than about 300 mm of annual precipitation may be subject to exceedingly long (years to decades) travel time due to the small amount of recharge.

C. Introduction:

Agriculture is a significant source of nitrate in groundwater in the Central Valley (CV) and is associated with leaching of fertilizers but also leaching of manure from confined animal facilities. During the past decade, millions of acres of croplands in the CV have been converted to orchards. Orchard crops have high nutrient demands; for example, almonds require approximately 150-200 lb/acre (170-225 kg/ha) nitrogen (N) annually and have replaced crops with lower nutrient requirements (i.e. alfalfa, cotton). Following this trend, the continued degradation of rural groundwater supplies is likely without intervention. The Irrigated Lands Regulatory Program (IRLP) developed by the Regional Water Boards (RWB) charges growers and their agricultural coalitions with implementing N management plans that are protective of groundwater quality by improving N use efficiency (NUE) and reducing N leaching to groundwater.

Previous research at the plot scale shows that high frequency low concentration (HFLC) fertigation can improve production through inducing higher NUE, potentially reducing impacts to groundwater. This project assesses commercial orchard farm-scale implementation of HFLC at a 143 acre (58 ha) almond orchard near Modesto, California. Measurements collected at the orchard span the root zone as well as include direct measurements of groundwater quality immediately underneath the orchard via a series of twenty monitoring wells. On-site measurements are used to develop vadose zone and groundwater models which assess drivers of trends in shallow groundwater quality and the long-term nitrate impacts of HFLC (Appendix L, Figure L1).

In May of 2022, we implemented a month-long pilot Agricultural Managed Recharge (AgMAR) experiment in a portion of the farm, where the orchard had been removed. With the existing array of vadose zone and groundwater quality sensors, along with the fertigation records collected from the farmer, we were able to leverage our past knowledge of the site to improve our understanding of how AgMAR affects groundwater nitrate concentrations. In future work, data collected during the AgMAR will be used in our existing computational models to assess the long-term water quality impacts of these kind of flooding events.

D. Objectives:

Objective #: 1
1.1 Continued to adaptively manage and adjust the High Frequency Low Concentration (HFLC) fertigation practice in a 58-ha (143 acre) commercial almond orchard. **1.2** Determine the corresponding land surface annual water and nitrogen fluxes into and out of the orchard (irrigation, fertigation, ET, harvest nitrogen) at the orchard scale, at measurement standards meeting and exceeding requirements for the Nutrient Management Plans required under Central Valley Regional Water Board (CV-RWB) Irrigated Lands Regulatory Program (ILRP).
Objective #: 2
Measure and assess the water (recharge) and nitrate (NO_3^-) flux and its spatiotemporal variability within and immediately below the root zone. Assess the need and potential options for installing a new vadose zone monitoring network. Continued development of an online data viewing application to help see trends in our collected data and assist with our understanding of the orchard.
Objective #: 3
Determine groundwater quality impacts and their spatiotemporal dynamics using a high-density groundwater monitoring well network and assess nitrate discharge from the orchard to groundwater using hydrogeologic and groundwater quality information. Investigate the use of Agricultural Managed Recharge (AgMAR) at the orchard to reduce groundwater N concentrations.
Objective #: 4
Assess relationship between measured water and nitrogen mass balance; measured vadose zone water and nitrogen fluxes, and measured groundwater quality (nitrate concentration) through development of a vadose zone - crop model, a groundwater model, and an integrated groundwater-vadose zone-crop model; apply models to evaluate scaled-up regional application of HFLC as potential new BMP capable of minimizing nitrate leaching to groundwater and improve groundwater quality at the regional scale.
Objective #: 5
Inform and discuss interim and final findings with grower-collaborator, ILRP agricultural coalition representatives, nut and other commodity grower representatives, and orchard growers; provide technical advice and findings to regulatory agency personnel, other ILRP stakeholders (e.g., environmental justice NGOs).

E. Methods:

Objective #1:

At the start of each growing season, we collaborated with the grower to adjust fertilizer application rates based on both the grower's yield predictions and our calculations for optimal nitrogen input. The total fertilizer amount was then distributed across as many applications as possible to maintain HFLC management. The grower's final fertilization plan was determined through a two-step process: an initial harvest estimate in March, following bloom, and a refined estimate in late April, after fruit set and plant tissue analysis. This approach combined formal plant nitrogen content analysis with the grower's experience and intuition regarding potential almond yield for the season. Additionally, the grower participated in semi-annual to annual meetings with the research team, ensuring they remained informed on project findings and gained insights on optimizing nitrogen application to minimize leaching to groundwater.

Water Mass Balance

Daily water mass balance calculations were conducted for each orchard block using the following equation:

$$R = P - ETa + IR + \Delta S$$

where:

- R is the estimated groundwater recharge,
- P is precipitation,
- IR is total irrigation, measured by the grower using a flow meter,
- ETa is actual evapotranspiration, and
- ΔS represents changes in soil moisture storage.

For the first six years of the project (2018 through growing season 2023), actual ET was estimated using the Cal-ETa model (Paul et al., 2018). In the final year (growing season 2024), we analyzed the uncertainty in these estimates by comparing Cal-ETa to alternative ET estimation methods. These included:

- OpenET (satellite-based, remotely sensed ETa),
- An eddy-covariance flux tower installed at the orchard, and
- The grower's irrigation management system (Ranch Systems).

This comparison allowed us to evaluate how uncertainty in ET estimates influenced the overall water balance calculations and affected predictions from the numerical models.

Nitrogen Mass Balance

Daily nitrogen mass balance calculations were performed for each orchard block using the following equation:

$N_{Losses} = (N_{applied}) + (N_{deposition}) + (N_{mineralization}) - (N_{uptake}) - (N_{denitrification})$ where:

- N-applied is the total nitrogen added through fertilizer,
- N-deposition accounts for atmospheric nitrogen deposition, which in the Central Valley typically ranges from 4.5 to 9 lb/ac/year (5 to 10 kg N/ha/year) but was set to 18 lb N/ac/year (20 kg N/ha/year) in this study due to nearby dairy operations (Harter et al., 2017)
- N-mineralization represents nitrogen released from soil organic matter,
- N-uptake is based on harvested kernel weights reported by the grower, calculated as:

(Kernel Weight [lb/ac])×68/1000 + 40 lb/ac (Brown et al., 2020, Muhammad et al., 2015) where 40 lb/ac (45 kg N/ha) accounts for annual tree growth, and

- N-denitrification accounts for 5% of applied nitrogen, removed from the system due to microbial denitrification.

We also measured, in each harvest season during the project period, the N-uptake directly by determining N content of kernel, shell, hull, and trash from representative sub-samples taken from harvest hauling trucks. This provided an alternative value to the kernel weight formula.

The annual nitrogen mass balance calculations provided a comprehensive assessment of nitrogen dynamics within the orchard, allowing us to evaluate the effectiveness of HFLC fertigation in reducing nitrate leaching. The calculations, with the kernel formula, are effectively identical to the method used by growers to comply with the Irrigated Lands Regulatory Program (ILRP) Nutrient Management Plan (NMP) requirements.

Objective #2:

Root zone monitoring was conducted at seven vadose zone monitoring stations randomly distributed throughout the orchard. All stations are located approximately 2 ft (60 cm) off the center of the tree-row, equidistant from the two adjacent trees, if possible, but always within the wetting circle of one or two micro-sprinkler or micro-drip emitters, approximately half-way between the center and the edge of the wetting circle. Each station was equipped with:

- Four tensiometers installed at depths of 110 in and 118 in (280 cm and 300 cm), continuously logging data every 15 minutes via a datalogger. These provided information about the quantity and direction of water flux in the deep vadose zone. However, due to issues arising from the tensiometers drying out, large amounts of noise in the resulting datasets, and uncertainty in soil hydraulic parameters, this data was not used in the analysis found in this report.

- Five pore water samplers placed at depths of approximately 1 ft, 2ft, 3 ft, 6 ft, and 9 ft (precisely at 30 cm, 60 cm, 90 cm, 180 cm, and 280 cm) to record vadose zone N concentrations.
- Access tube to 10 ft used for manual water content measurements at the same five depths using a neutron probe tool.

Pore-water samples (pore water sampled N-concentration and neutron probe water content) were collected approximately every two weeks during the growing season, and approximately monthly in the winter months. These data were used to assess real-time field conditions in response to HFLC fertigation and aided in calibrating numerical models.

Twice annually, before and after the growing season, soil samples were taken from 0 ft – 1 ft (0 cm – 30 cm) and from 1ft – 2 ft (30 cm – 60 cm), at 9 random locations in each of the five orchard blocks within the orchard farm and composited into 3 samples at each depth, for analysis of soil nitrate and ammonia.

All collected data were accessed by the team and the grower through an interactive data portal. This dashboard has improved communication and collaboration among project members by providing a centralized platform for data visualization and analysis.

Objective #3:

Groundwater Sampling Methods

Groundwater monitoring wells were sampled twice quarterly, beginning immediately after construction in April 2017, to assess groundwater depth, nitrate concentrations, and overall water quality. The following parameters were measured at each sampling event:

- Groundwater depth
- Nitrate concentrations
- Water quality indicators, including pH, electrical conductivity (EC), redox potential, and temperature

A total of 20 groundwater monitoring wells were distributed throughout the orchard to capture spatial variability in nitrate concentrations. Sampling followed standardized procedures to ensure consistency in data collection over time.

AgMAR Implementation Methods

In May 2022, an Agricultural Managed Aquifer Recharge (AgMAR) trial was conducted in the northeastern orchard block of the farm, after removal and recycling of trees. The recharge event involved flooding three 0.17 acre (0.07 ha) recharge basins at the orchard farm for a period of 29 days, applying approximately 30 ft (9 m) of water in each basin.

Following the AgMAR event, groundwater samples were collected from the wells directly downgradient from the flooded area to assess changes in nitrate concentrations. The monitoring schedule remained consistent with the established groundwater sampling protocol, ensuring long-term tracking of nitrate dynamics in response to AgMAR implementation.

Objective #4:

Vadose Zone Model Development and Calibration

To simulate water and nitrate fluxes through the unsaturated zone, we developed HYDRUS1D models for the orchard, utilizing soil texture information from 20 soil cores collected during groundwater monitoring well installation in 2017. Each core was simulated independently, resulting in 20 separate modes.
The boundary conditions for the simulations were assigned based on:

- Precipitation data from the nearest two weather stations and from one spatially interpolated online weather service product.
- Evapotranspiration data from the nearest CIMIS station using the crop coefficient developed for almonds by University of California, from OpenET™, from an on-site ET tower (in 2024).
- Irrigation records provided by the grower.
- Fertilizer application records, including the switch to HFLC fertigation in 2018.

Using (and repeating) climate, irrigation, and nutrient management data from 2013 to 2017 (pre-HFLC) and from 2018 - 2022 (with HFLC), the models were run over a 142-year simulation period (1957–2099) to evaluate both historical (pre-HFLC up to 2017) and long-term future nitrogen loading dynamics (with HFLC since 2018).

During the most recent reporting period, additional calibration was performed using measured vadose zone data collected at the orchard since 2018. Calibration included:

- Soil moisture content data from neutron probe measurements.
- Pore-water nitrate concentrations from vadose zone samplers.
- Optimization of hydraulic flow and root uptake parameters using the Parameter
- Estimation and Simulation Tool (PEST), an industry standard nonlinear parameter estimation software

This calibration process refined the models to better capture water and nitrate transport through the vadose zone and improved the understanding of spatial variability in nitrate loading to groundwater.

Groundwater Model Development

A 3D MODFLOW-based groundwater flow model was constructed to simulate the movement of water and nitrate within the unconfined aquifer beneath the orchard. The model domain spans approximately 1 mile by 0.7 miles (1.5 km by 1 km), encompassing the entire orchard and upgradient areas. The model extends to a depth of 130 ft (40 m), terminating at the Corcoran Clay confining layer.

Key components of the groundwater model include:

- Flow simulation using MODFLOW, incorporating transient boundary conditions based on measured groundwater elevations.
- Contaminant transport modeling with MT3D, allowing for simulation of nitrate migration.
- Groundwater age and particle tracking using MODPATH, to assess source areas, travel times and long-term nitrate trends.
- Geologic heterogeneity representation using T-ProGS, a transition probability-based stochastic modeling approach for alluvial sediment distribution.
- The hydraulic conductivity distribution was calibrated against flux estimates from the MERSTAN regional groundwater model developed by the USGS (Phillips et al., 2015). Recharge and nitrate flux inputs to the groundwater model were derived from the calibrated HYDRUS1D vadose zone models, ensuring consistency between surface and subsurface processes.

The hydraulic conductivity distribution was calibrated against flux estimates from the MERSTAN regional groundwater model developed by the USGS (Phillips et al., 2015). Recharge and nitrate flux inputs to the groundwater model were derived from the calibrated HYDRUS1D vadose zone models, ensuring consistency between surface and subsurface processes.

AgMAR Integration into Vadose Zone and Groundwater Models

The groundwater model was further adapted to incorporate the AgMAR recharge event that occurred in May 2022. This involved:

- Simulating a 29-day flooding event over recharge basins in the northeastern orchard block.
- Integrating measured groundwater nitrate concentrations from the three nearest monitoring wells to validate model predictions.
- Running scenario-based AgMAR simulations to evaluate long-term nitrate dilution potential.

Additional AgMAR scenario simulations were conducted to assess the impact of varying infiltration volumes on groundwater quality. The model was used to determine the threshold at which applied water dilutes nitrate concentrations rather than mobilizing stored nitrogen, helping refine recommendations for future AgMAR applications. This work is in progress and will be completed as part of the follow-on project.

Objective #5:

M.S. theses, manuscripts in preparation:

Jordan, S., T. Harter, I. Kisekka, H. Dahlke, 2024, Monitoring and Assessing Groundwater Nitrate Impacts across Scales in Response to an Agricultural BMP: Evaluating Data Worth of Water and Nitrogen Mass Balance, Vadose Zone Monitoring, and Groundwater Monitoring. M.S. thesis, University of California Davis.

Haynes, H., T. Harter, H. Dahlke, L. Foglia, 2022, Modeling Non-point Source Nitrate Groundwater Contamination at an Almond Orchard in the Central Valley, California. M.S. thesis, University of California Davis.

Published in peer-reviewed journals:

Alley, W.M., S.B. Megdal, T. Harter, 2024. The federal role in addressing groundwater depletion. Groundwater, https://doi.org/10.1111/gwat.13454 (open access)

Kourakos, G., T. Harter, H.E. Dahlke, 2024. ICHNOS: A universal parallel particle tracking tool for groundwater flow simulations, SoftwareX 28, 101893, https://doi.org/10.1016/j.softx.2024.101893 (open acces)

Raij-Hoffman, I., O Dahan, H.E. Dahlke, T. Harter, I. Kisekka, 2024. Assessing nitrate leaching during drought and extreme precipitation: Exploring deep vadose-zone monitoring, groundwater observations, and field mass balance. Water Resour. Res. 60(11):e2024WR037973, https://doi.org/10.1029/2024WR037973 (open access)

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Zhou, T., E. Levintal, G. Brunetti, S. Jordan, T. Harter, I. Kisekka, J. Šimunek, H.E. Dahlke, 2023. Estimating the impact of vadose zone heterogeneity on agricultural managed aquifer recharge: A combined experimental and modeling study. Water Research 247:120781, https://doi.org/10.1016/j.watres.2023.120781 (open access)

Yao, Y., J.R. Lund, and T. Harter, 2022. Conjunctive management for agriculture with groundwater salinity. Water Resour. Res. 58(10), https://doi.org/10.1029/2021WR031058 (open access)

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Kourakos, G. and T. Harter, 2021. Simulation of unconfined aquifer flow based on parallel adaptive mesh refinement. Water Resour. Res. 57(12), e2020WR029354, https://doi.org/10.1029/2020WR029354 (open access)
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F. Data/Results:

Groundwater Nitrate Trends at the Study Site

Long-Term Trends in Groundwater Nitrate Concentrations

Groundwater nitrate concentrations at the orchard have shown a consistent increasing trend since monitoring began in 2017. The median concentration has risen from approximately 20 mg/L NO_3-N to 40 mg/L NO_3-N in 2024, with an average annual increase of ~3 mg/L per year (Figure 1). Despite improved nitrogen management under High-Frequency Low-Concentration (HFLC) fertigation, groundwater nitrate concentrations have continued to rise due to historical nitrogen loading, long vadose zone travel times, and the slow movement of existing nitrate contamination in groundwater. Temporarily higher concentrations of nitrate were associated with young orchards (less than 5 years old), which averaged 39 mg N/L, while average nitrate concentrations in groundwater associated with mature orchards averaged 26 mg N/L (Appendix L Figure L2).

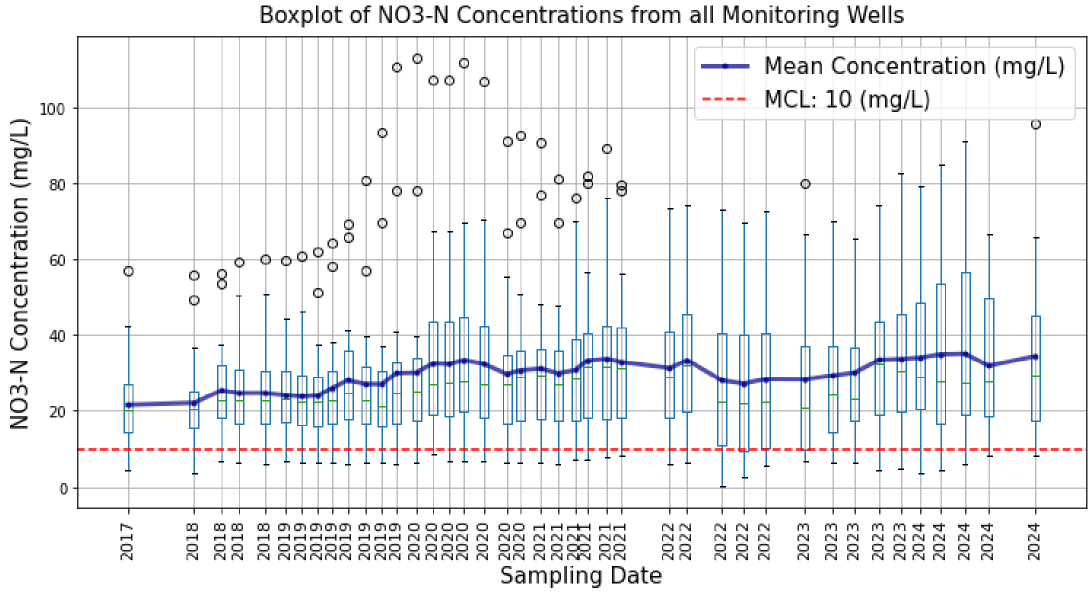

Figure 1: Groundwater nitrate-N measured in the shallow groundwater monitoring well network. For each sampling date, the box represents the 25th and 75th percentile, the horizontal line represents the median, the whiskers represent the 5th and 95th percentile.

Measuring and Modeling NUE Under HFLC Fertigation: Linking Mass Balance and Modeled Leaching

HFLC fertigation was implemented to improve NUE by aligning nitrogen applications more closely with tree demand. Throughout the project, nitrate leaching was assessed using both direct field measurements and numerical modeling, allowing for a comprehensive evaluation of HFLC impacts on nitrogen fate and transport.

Orchard farm annual yields in 2013-2017, prior to HFLC, averaged 2190 lb/ac of kernels (149 lb N/ac, 167 kg N/ha). Average yield from 2018 to 2022 (with HFLC, period used for vadose zone and groundwater simulations) increased to 2460 lb/ac of kernels (167 lb N/ac, 187 kg N/ha). For the entire 2018 to 2024 period, average yields with HFLC increased slightly less to 2320 lb/ac of kernels (158 lb N/ac). Over the period of record (2013-2024), farm average yields (not including young orchard blocks) exceeded 2,500 lb/ac (2,800 kg/ha) of kernels in 2018 and 2020 but were as low as 1,800 lb/ac (2000 kg/ha) of kernels in 2019 and 2023.

Prior to HFLC implementation (2013-2017), the orchard had an average reported NUE of 74%, with total nitrogen applications averaging 222 lb-N ac^{-1} yr^{-1} (249 kg-N ha^{-1} yr^{-1}). Following the transition to HFLC, reported NUE increased to 92%, while total applied nitrogen was reduced to 168 lb-N ac^{-1} yr^{-1} (188 kg-N ha^{-1} yr^{-1}) without impacting yield (data exclude young orchards). For the period from 2018-2022 (HFLC period of the simulation model), measured N fertilizer applications with HFLC averaged 189 lb-N ac^{-1} yr^{-1} (212 kg-N ha^{-1} yr^{-1}) with a measured NUE of 86%. Modeled results aligned closely with these measured trends, with simulated NUE increasing from 76% (pre-HFLC, 2013-2017) to 84% (with HFLC, 2018-2022). Note that the average NUE in 2022 – 2024 was higher than in 2018-2021, hence the different averages for 2018-2022 and for

2018-2024. Annual orchard block details for N inputs and outputs for 2013 to 2024 can be found in Appendix Table L1.

Improvements in NUE were reflected in measured reductions in soil nitrogen storage and nitrate concentrations in the vadose zone. Post-harvest total soil nitrogen in the upper 60 cm of orchard soils declined from approximately 100 lb N/ac (112 kg N/ha) pre-HFLC to approximately 20 lb N/ac (22 kg N/ha), indicating a significant reduction (p-value < 0.01) in residual nitrogen available for leaching. Additionally, average pore-water nitrate concentrations in the shallow vadose zone showed a statistically significant (p-value < 0.05) downward trend from 2018 to 2024. Both results are consistent with the nitrogen mass balance above in that nitrogen losses (and therefore leaching concentrations) decreased under HFLC fertigation (Figures 2, 3).

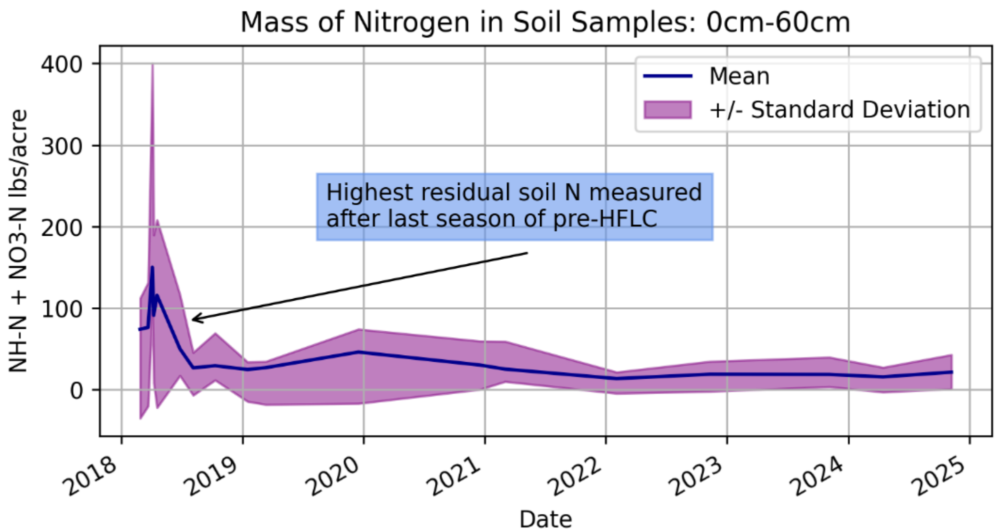

Figure 2 Mass of inorganic soil nitrogen in the upper two feet (60 cm), measured in soil core samples taken immediately before and after the growing season in February and November of most years. From each of five orchard blocks, nine locations are sampled and composited into three samples per block. Shown are mean and standard deviation of composite samples across all blocks.

Vadose zone and groundwater modeling results reinforced these findings, providing a broader view of nitrate transport and groundwater quality response to HFLC fertigation. Vadose zone model simulations showed that nitrate concentrations leaching from the root zone to the water table decreased substantially following HFLC adoption. Prior to HFLC, modeled nitrate concentrations at the water table peaked at 47 mg/L NO_3-N, but under HFLC, these values declined to an average of 26 mg/L NO_3-N, representing a 45% reduction in nitrate loading over approximately 10 years (Figure 4). This decrease was driven by both improved NUE and reduced fertilizer application rates, leading to lower nitrate mass available for leaching.

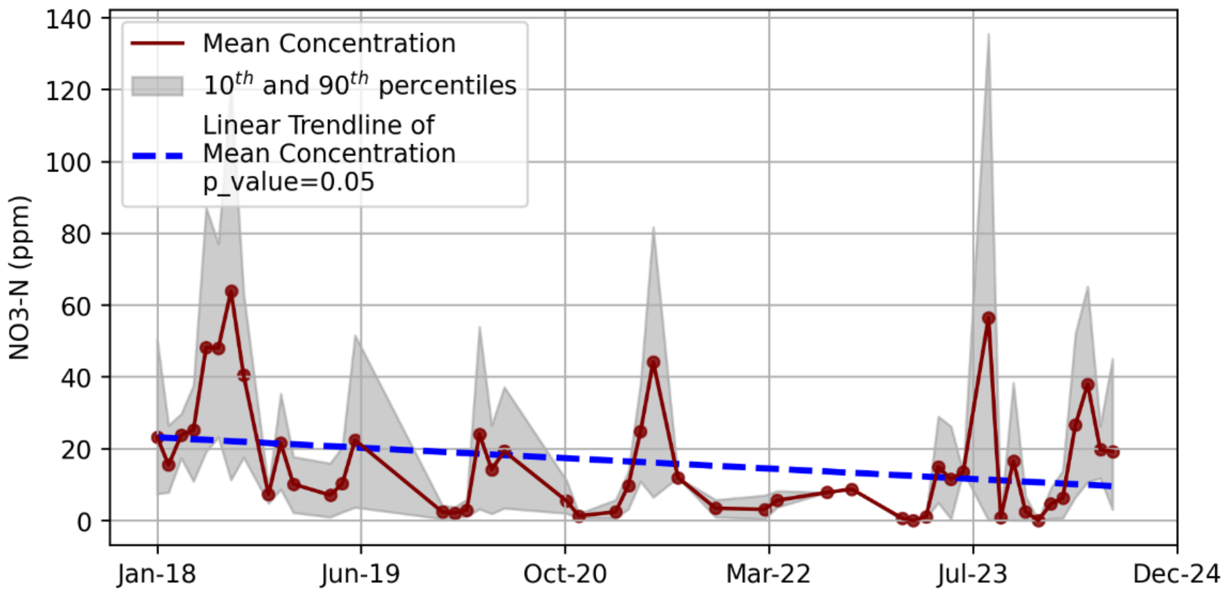

Figure 3: Vadose zone soil solution nitrate, measured in the suction lysimeter network from 0 – 60 cm (seven vadose zone monitoring stations).

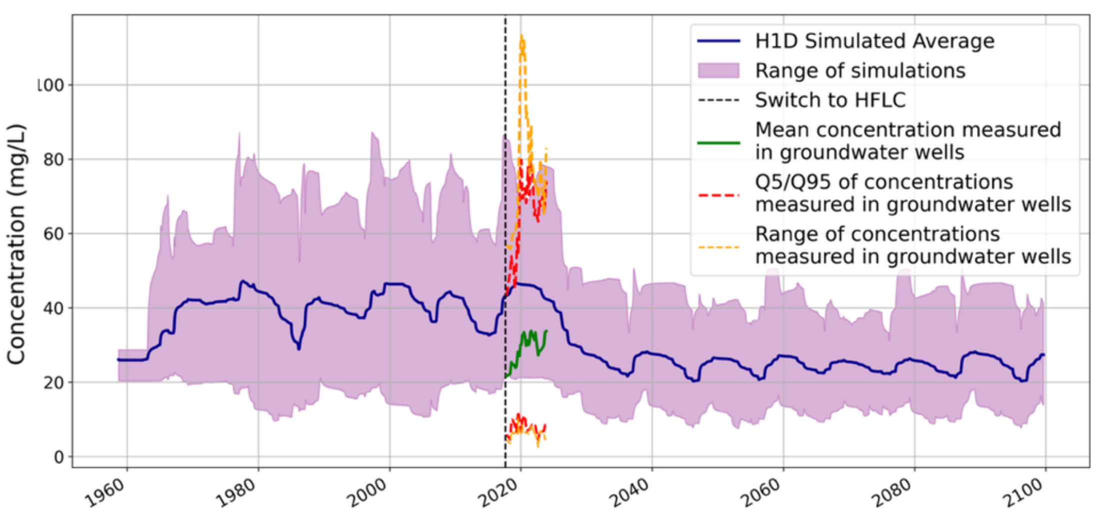

Figure 4: Mean and range of simulated nitrate-N concentration in recharge at the water table, 20 ft below ground surface (mean over twenty simulated locations within the orchard, one at each monitoring well site, honoring the observed stratigraphy) under pre-2018 management practices and with HFLC from 2018 onward. Measured concentrations in shallow groundwater monitoring wells are shown for 2017 – 2024 (total range, 5th and 95th percentile, mean). Simulated results for recharge nitrate are taken from the calibrated vadose zone model (Version 2024, Jordan et al., 2024). The calibrated vadose zone model assumed no nitrate in the vadose zone in 1960 and assumed pre-HFLC water and nitrogen management (as measured by the grower in 2013-2017) over the entire pre-2018 simulation period. Results show that it takes approximately 5 years for the mean nitrate in recharge at the water table to begin to increase and about 10-15 years for the full effect of nitrate losses to be realized in recharge at the water.

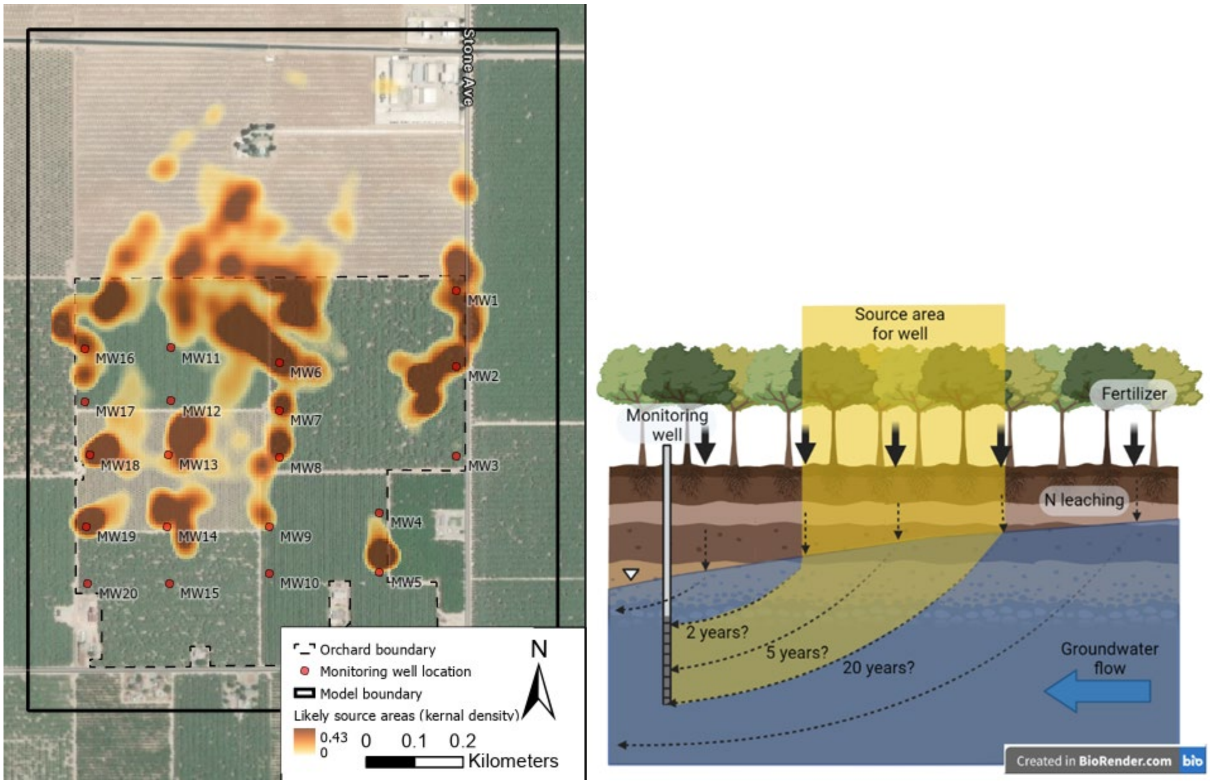

Figure 5: Left diagram: Conceptual definition of a "source area" of a monitoring well – the specific land area where recharge originates that eventually reaches a specific monitoring well. Right diagram: Likely source areas of water sampled from the twenty monitoring wells, estimated by Monte Carlos simulation with the MODFLOW-Modpath groundwater flow and transport model (recharge rates from the uncalibrated vadose zone model). The uncertainty arises by accounting for the uncertainty of the specific heterogeneous sedimentary pattern of the aquifer through multiple random realizations of aquifer heterogeneity. All realizations honor the specific geology determined at the 20 well sites during well drilling and, at the surface, in soil maps (Gurevich et al., 2021, Haynes et al., 2022)

The groundwater model extended this analysis to predict how these reductions in nitrate leaching will translate to long-term changes in groundwater quality. The model confirmed that much of the source area of the monitoring wells lies within the perimeter of the orchard farm with some monitoring wells being impacted by adjacent roads and orchards (Figure 5). Results indicate that HFLC fertigation will lead to meaningful improvements in groundwater nitrate concentrations over time, with measurable reductions in the upward trend expected to begin over the next decade (Figure 9). As older nitrate-laden water is gradually replaced by lower-nitrate recharge from HFLC-managed areas, overall groundwater quality is projected to eventually improve. However, variability in response is expected, particularly in areas with historically high nitrate leaching or recent tree replanting, where longer travel times may delay observable reductions. Despite these localized differences, model results support HFLC fertigation as a viable solution for reducing agricultural nitrate loading to groundwater, with both measured and modeled data confirming its effectiveness in improving NUE and reducing nitrate losses.

Statistical Relationship Between Applied Nitrogen and Groundwater Nitrate

A statistically significant relationship was observed between mass balance-estimated leaching prior to implementation of HFLC, and 2018-2022 measured groundwater nitrate concentrations ($p = 0.04$, $R^2 = 0.91$) at the orchard block scale (Figure X). Blocks with higher estimated nitrogen leaching (from the mass balance) consistently exhibited higher groundwater nitrate concentrations, reinforcing the link between fertilizer application rates and long-term nitrate loading to the aquifer. This trend persisted across multiple years and climate conditions, demonstrating that orchard nitrogen management is the primary driver of nitrate concentrations in shallow groundwater.

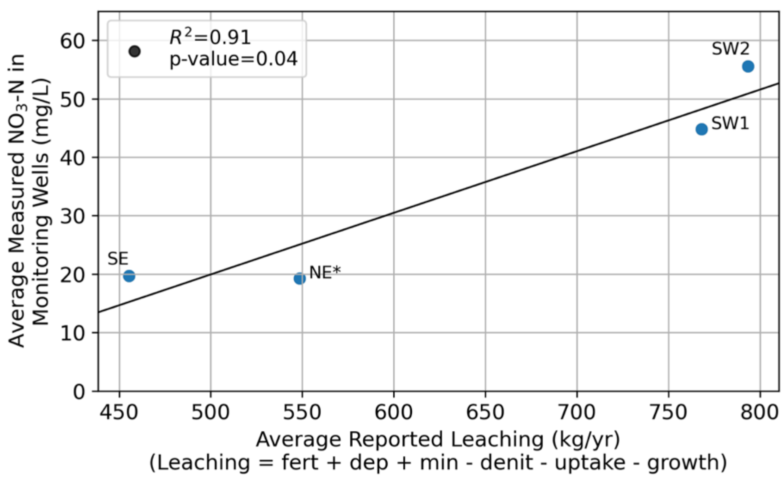

Figure 6: Linear regression between average reported leaching and the average measured NO3-N concentrations measured within each orchard block. NE1 and NE2 reported N balance was done as a single "NE" block; therefore, they could not be separated for this analysis. The NW block was not considered due to data quality issues; for pre-HFLC years, the reported NUE was unrealistically high in this block (>90% on average)

Spatial Variability in Groundwater Nitrate

Nitrate concentrations varied significantly across the orchard, with well concentrations ranging from non-detect (<2 mg/L NO_3-N) to over 100 mg/L NO_3-N (Appendix L, Figure L3). Two key factors were found to influence this spatial variability:

1. *Tree Replanting and its Influence on Nitrate Leaching.*
   Orchard blocks that underwent tree replanting exhibited some of the highest observed increases in groundwater nitrate concentrations. The SW1 and NE1 blocks showed increases of 52% and 150%, respectively, within two years of replanting. These effects were not confined to orchard boundaries—wells near the northwestern boundary exhibited a 53% increase in peak nitrate concentrations following replanting of a neighboring orchard, as inferred from satellite imagery. This highlights how management practices beyond the orchard itself can strongly influence groundwater quality (Appendix L, Figure L2).
2. *Variability in Nitrogen Use Efficiency (NUE) Across Orchard Blocks.*
   Blocks with lower NUE (less efficient nitrogen uptake) exhibited higher nitrate

leaching rates, resulting in elevated groundwater nitrate concentrations. Simulations calibrated to measured NUE also demonstrated a strong relationship between modeled NUE and nitrate leaching, reinforcing the role of nitrogen uptake efficiency in controlling groundwater contamination.

Nitrogen Mass Balance as a Monitoring Tool

A central component of this study was using a nitrogen mass balance approach to estimate nitrate leaching losses. While high-resolution groundwater monitoring and numerical modeling provide detailed insights into nitrate transport, they are not feasible at every farm. Instead, mass balance methods offer a cost-effective, scalable alternative for estimating nitrogen leaching at the orchard scale.

To assess the accuracy of the manual mass balance approach, we compared its predictions to measured groundwater nitrate concentrations and modeled nitrate leaching rates from the HYDRUS1D models.

The results show that, on average, the mass balance estimates provided a reasonable approximation of groundwater nitrate trends. In particular:

- Orchard block-scale and orchard farm-scale groundwater nitrate concentrations aligned with predicted nitrogen leaching from the mass balance.
- Model predictions, which were calibrated with the mass balance calculated NUE, accurately captured the spatial variability in N leaching across the orchard.
- As was discussed previously, there was a strong correlation between block-level NUE and groundwater nitrate concentrations, reinforcing that orchard-scale nitrogen balance estimates are useful for predicting nitrate trends.
- While the mass balance could not capture sub-block scale spatial variability, it effectively estimated average N leaching rates at the orchard block and orchard farm scale.
- Reductions in leaching measured by the vadose zone monitoring network (pore-water N concentrations and soil residual N) aligned with the mass balance predicted increase in NUE following the switch to HFLC.

These findings suggest that a properly constrained mass balance approach—using detailed irrigation, fertilization, and crop yield data—can provide a viable method for estimating N leaching at other agricultural sites.

AgMAR and Groundwater Quality Impacts

Agricultural Managed Aquifer Recharge (AgMAR) was tested at the orchard in May 2022, when the northeastern block was flooded for 29 days, introducing approximately 900 cm of water into three recharge basins. This provided an opportunity to assess how managed recharge influences groundwater nitrate concentrations.

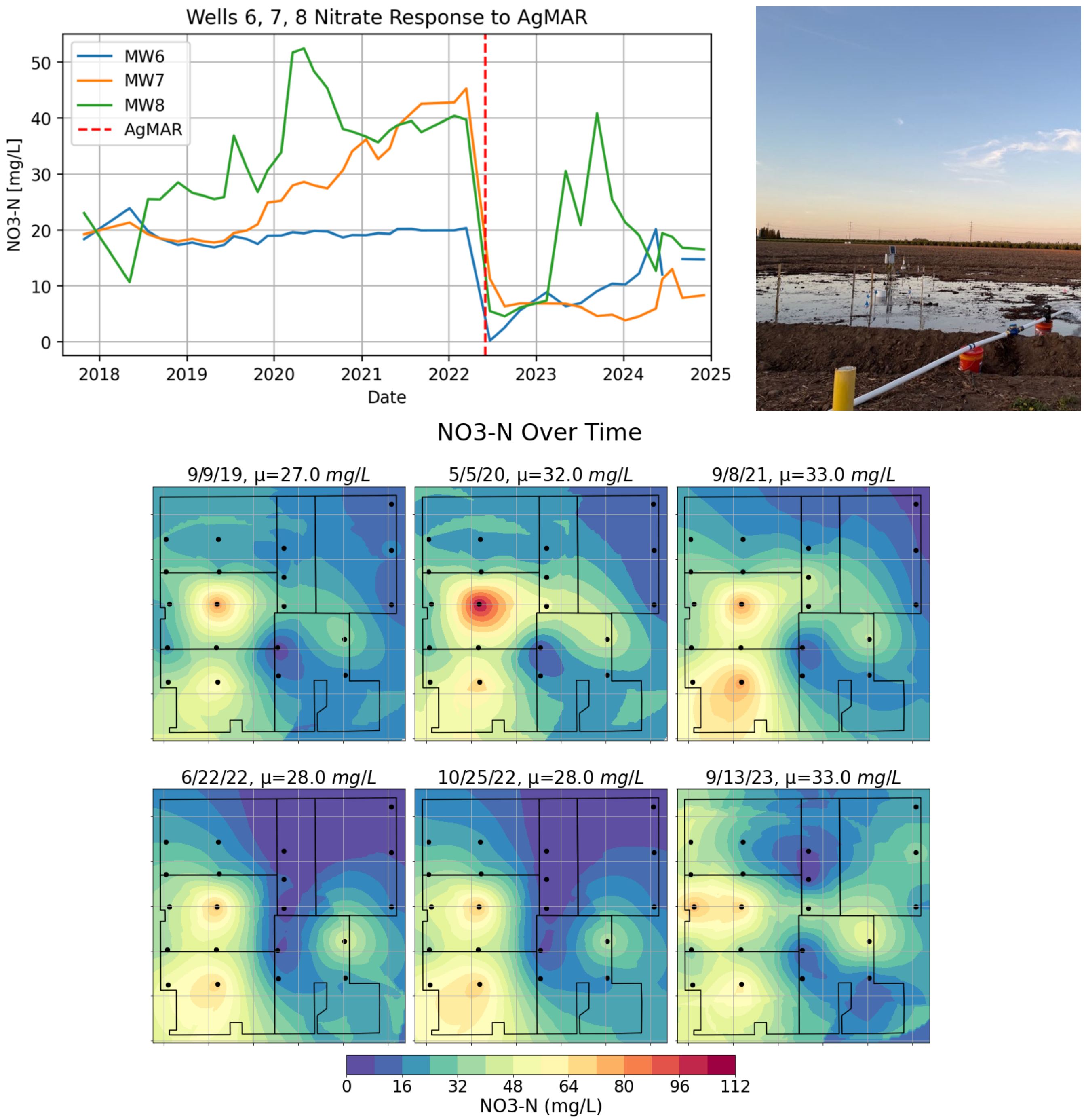

Figure 7: TOP - Nitrate-N concentration in three monitoring wells of the NE block, which was removed after harvest in 2021. In spring of 2022, an AgMAR (agricultural managed aquifer recharge) pilot experiment was implemented adjacent to each of the monitoring wells (see detailed site description in Zhou et al., 2023). BOTTOM - Historic Spatial nitrate concentration in the orchard (left), each black dot represents one of the 20 groundwater monitoring wells. Area circled in red corresponds to the three wells that were flooded during the AgMAR event (seen in the picture on the right), where a distinct dilution signal can be seen following the event.

Nitrate concentrations rapidly decreased in three groundwater wells downgradient of the recharge basins, showing a strong dilution effect in the aquifer. Two of these wells remained below their pre-AgMAR levels of nitrate for the remainder of the project period, however, the third well showed a temporary increase back to its pre-AgMAR concentration within 1.5 years before again declining (Figure 7).

G. Discussion and Conclusions:

This study evaluated the effectiveness of High-Frequency Low-Concentration (HFLC) fertigation as a best management practice for reducing nitrate leaching in a commercial almond orchard. Using extensive field monitoring, nitrogen mass balance assessments, and calibrated vadose zone and groundwater models, we assessed nitrogen use efficiency (NUE), nitrate transport in the vadose zone and in shallow groundwater, and long-term groundwater quality impacts. The results confirm that HFLC fertigation improves nitrogen management and significantly reduces nitrate leaching. Results also highlight the long timescales required for these reductions to translate into improved groundwater quality, even under relatively shallow (20 ft bgs) water table conditions – many areas of the Central Valley have deeper water table.

The outcome of this work to date informs three audiences of the CDFA Fertilizer Research and Education program: growers, environmental/agricultural consultants, and regulatory agencies and the public including domestic well owners and the public water supply utilities impacted by groundwater nitrate pollutions. We discuss findings of most importance to these stakeholders separately.

Key Discussion for Growers:

HFLC has shown promising results during the seven-year span of this project (2018-2024). Lower applied nitrogen and higher NUE has led to measurable decreases in soil nitrogen storage and pore-water nitrate concentrations, and simulations indicate that there will be a 45% reduction in nitrate leaching at the water table from the vadose zone. In the words of the grower "I have felt we have not seen any reduction in yield and N leaf tissue levels have remained strong despite reducing N rates slightly."

On average, reported NUE has increased by 18% and kernel yields have increased by 6 -12% when compared to the previous five years of pre-HFLC orchard management. This efficiency gain was achieved through adaptive nitrogen management tailored to individual orchard blocks, allowing for a reduction in applied nitrogen from about 220 lb-N/ac/yr to about 170 lb-N/ac/yr (~250 kg-N/ha/yr to ~190 kg-N/ha/yr) across all blocks of varying age, not including young orchards, without compromising yield. Significant savings in nitrogen fertilizer applications have been achieved, nearly 17.5% (33 lb N/ac), on average, between 2018 and 2022 and over 30% (54 lb N/ac), on average, between 2018 and 2024. Over the 7 seasons (or 5 season w/o 2023-2024) with HFLC, on 143 acres and at $0.65/lb N, this amounts to $5,000 ($3,100) in savings on fertilizer cost per year, respectively. Over 10 years, this would far exceed the cost of the automated fertigation system that was installed to enable HFLC.

For nutrient management, the grower initially estimates season total expected yield from inspections during blossom, in February, and again at fruit-set, in April, also using information on orchard age, status, and climate conditions. The grower further monitors tree nutrient status following the UC Davis Early-Sampling protocol and applies it to make subsequent in-season nutrient management adjustments for May to July to match expected yield (Saa et al., 2014).

Key Discussion for Environmental / Agricultural Consultants:

Nitrate N in both the unsaturated zone and in shallow groundwater is highly variable (Figures 1, 3, Appendix L Figure L3), suggesting that the use of 7 vadose zone monitoring stations and 20 groundwater monitoring wells across the orchard farm was needed to characterize farm-scale leaching (Gurevich et al., 2021).

Using the nitrate variability observed at site, we computed the confidence interval of the mean nitrate in groundwater across the orchard farm ("farm scale" groundwater nitrate) as a function of the number of monitoring wells randomly placed across the farm. We found significantly larger uncertainty about farm scale (mean) nitrate when 2 to 5 monitoring wells were used than with 10 monitoring wells or more (Figure 9).

Average nitrate specifically in the sand/gravel core samples of the shallow aquifer, obtained during monitoring well drilling, was much better correlated with monitoring well nitrate than nitrate in finer-textured core samples. This confirms that monitoring well water quality reflects that in the coarsest aquifer sediments with the fastest lateral flow (*ibid.*). Importantly, though, the fraction of coarse vs fine sediments in the highly heterogenous 40 ft core profiles spanning both the unsaturated zone and the shallow saturated zone had no predictive value of shallow groundwater nitrate. The numerical simulation models confirm that stratigraphic variability has limited impact on groundwater nitrate variability (Haynes et al., 2022).

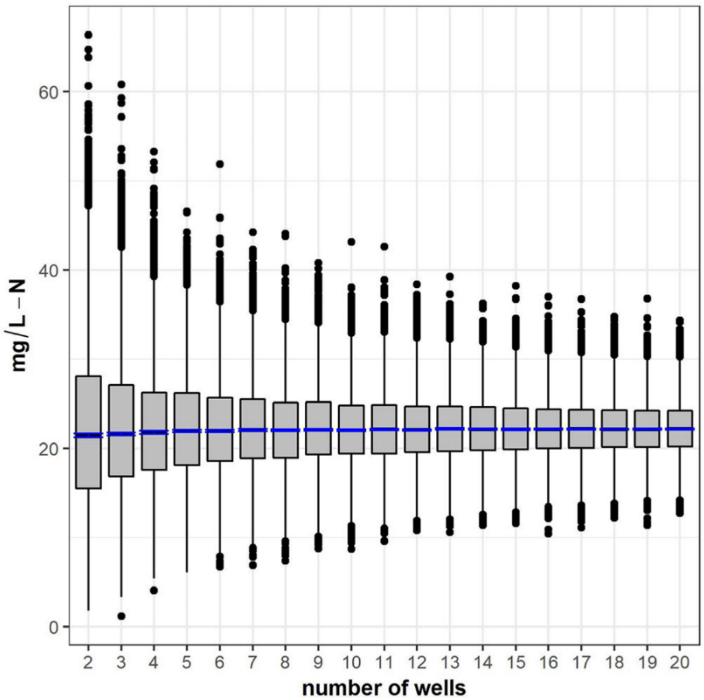

Figure 8: Distribution of sample means (boxplots indicating 5th, 25th, 50th, 75th, and 95th percentile) as a function of the number of monitoring wells, using Monte Carlo simulation (Gurevich et al., 2021).

Numerical models suggest that although nitrate concentrations quickly decrease in the shallow vadose zone, there will be an up to 30-year delay between the start of HFLC and an observable decrease in groundwater nitrate concentrations (Figure 9, water table at 20 ft below ground surface [bgs], groundwater monitoring wells screened to 40 ft bgs). This delay is caused by the long transport time that nitrogen experiences between surface application and recharge at the water table, given the low recharge rates. Groundwater movement at the site is also relatively slow given the relatively small hydraulic gradient across the orchard and common to this area near the groundwater-gaining confluence of the Tuolumne and San Joaquin Rivers. Our unsaturated zone models suggest that the vadose zone transport time alone can be between 5 and 15 years (Figure 4), depending on soil types (i.e. water and N move slower in clayey soils than in sandy ones).

Spatial variability in groundwater nitrate was primarily driven by block-level differences in NUE (Figure 6) and cycles of tree replanting (Appendix L, Figures L2, L5), both within the study site and in neighboring orchards. Blocks with lower NUE exhibited consistently higher nitrate concentrations, and wells beneath or near recently replanted areas showed sharp increases in nitrate levels. This is likely due to reduced irrigation efficiency in young orchards, which mobilized stored nitrogen in the vadose zone. While soil texture influenced modeled transport rates, it was not a strong predictor of nitrate concentrations, reinforcing that management practices are the dominant control on groundwater nitrate variability. These findings emphasize the importance of targeted nitrogen management, particularly in historically lower-NUE areas and during orchard replanting, to further minimize nitrate leaching.

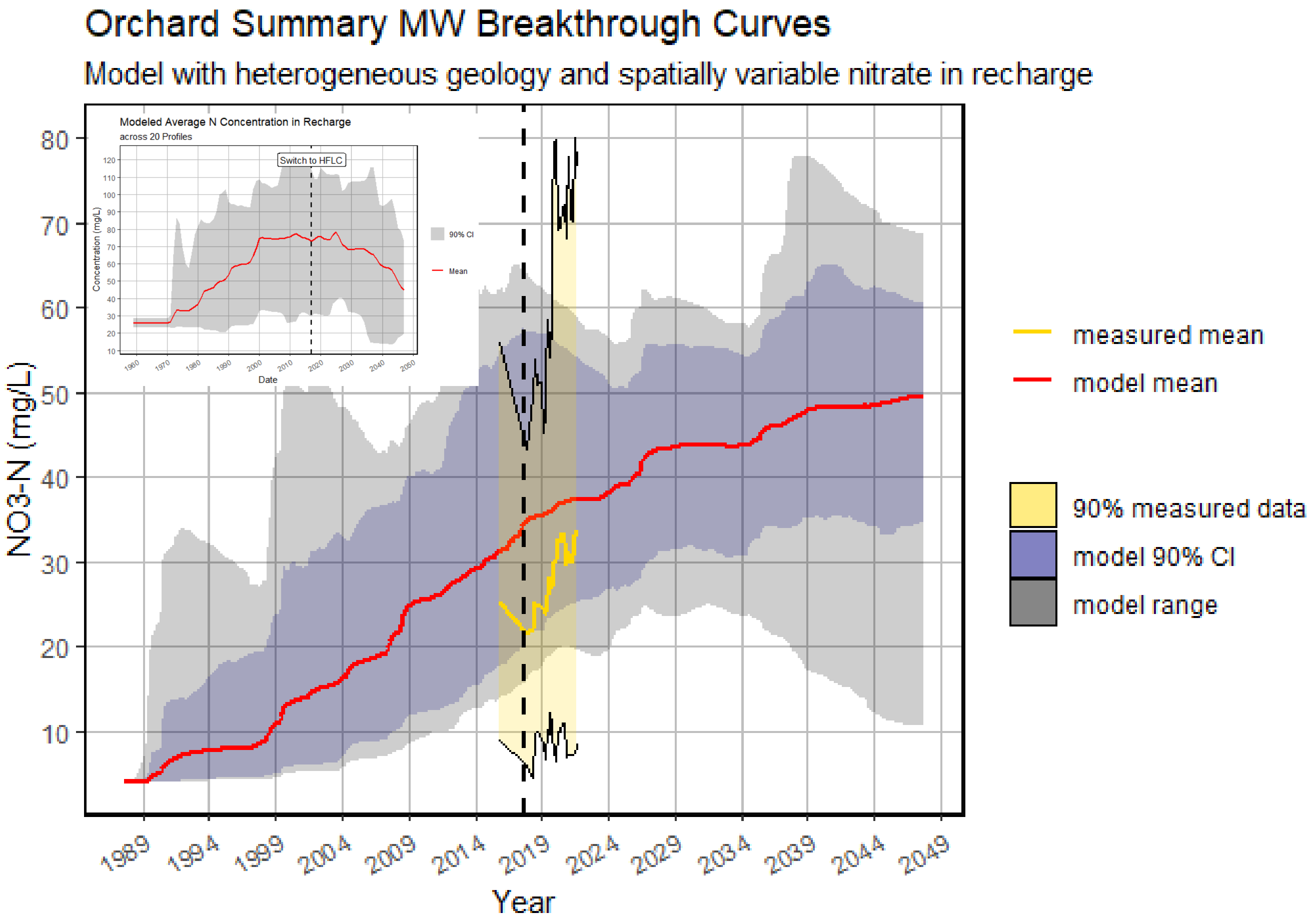

Figure 9: Measured and simulated groundwater nitrate-N concentrations (Version 2022 groundwater flow and transport model using MODFLOW and MT3D, Haynes et al., 2022), simulating a period from 1989 to 2049. The model, for simplification, assumes no nitrate in groundwater prior to 1989. The groundwater model is driven by recharge and nitrate concentrations of the uncalibrated vadose zone model, which simulated the period from 1960 to 2050. The uncalibrated vadose zone model assumes no nitrate in the vadose zone prior to 1960 (Version 2022, insert, upper left). The uncalibrated vadose zone model results indicate that it takes over a decade (after 1970) for nitrate to begin affecting recharge concentrations at the water table, at 20 ft below ground surface, and about four decades to reach equilibrium conditions (no increasing trend) at the water table, under pre-HFLC management conditions. Groundwater concentrations do not reach equilibrium conditions. Rising groundwater nitrate concentrations in monitoring wells begin to slow their upward trend approximately 10-15 years after the switch to HFLC management (around 2030), but do not begin to decline until after 2050 (Haynes et al., 2022). Note, that in the uncalibrated vadose zone model (Version 2022), the maximum mean recharge concentration of nitrate-N under pre-HFLC conditions is nearly twice as high (nearly 80 mg N/L) than in the calibrated model (45 mg N/L,compare insert above to Figure 4). The uncalibrated version underestimated recharge, leading to significantly longer travel times and higher nitrate concentrations at the water table than the calibrated vadose zone model. In future work the integrated vadose zone – groundwater model will be updated. Based on the outcome from the calibrated vadose zone model and the groundwater simulations here, we hypothesize that the measured increasing trend in groundwater nitrate concentration will begin to significantly flatten and even decline within the next five years, and not reach mean nitrate concentrations much exceeding current levels (less than 40 mg N/L), especially after discounting effects from neighboring orchards (Figure 5).

Other causes of the large variability in groundwater nitrate may stem from block-scale non-uniformity of fertilizer and irrigation application (young orchard blocks, old orchard blocks). On the other hand, despite the highly heterogenous local geology, which are embedded in the simulations, modeling confirms the field observations: the highly variable vadose zone and groundwater nitrate concentrations may be more driven by the variability in water and nitrate leaching from the root zone, then sedimentary heterogeneity within the deeper vadose zone or shallow groundwater.

Calibration of the vadose zone model was critical to match both, observed water content (Appendix L, Figure L4) and observed nitrate concentrations and variability in the upper 10 ft of the vadose zone (Figure 3). Calibration was most aided by calibration of the boundary conditions and less so by the calibration of the hydraulic parameters characterizing the wide range of soil textures from which the models were built. Regularly measured vadose zone water content measurements to 10 ft allowed us to properly pick precipitation and ET data defining the top boundary such that seasonal and inter-annual soil water content variations across the orchard farm were properly simulated. The uncalibrated model yielded soil moisture conditions that were too dry throughout the 10 ft profile, restricting ET and not leading to the nearly perfect match of measured and simulated ET in the calibrated model.

From a discrete set of 9 measured (and equally plausible) precipitation and ET data series combinations, manual calibration to water content selected the time series with the highest long-term precipitation and the lowest long-term ET. Importantly, calibrated recharge values were significantly higher than in the uncalibrated vadose zone model, although still less than one-half foot per year (Appendix L, Figure L6). With fertilizer applications fixed as input and further calibration of root nitrate uptake to measured harvest, residual nitrate mass varied little between uncalibrated and calibrated vadose zone model. Hence, nitrate concentrations in leachate from the root zone were highly sensitive to the simulated recharge amounts. Calibration of the precipitation and ET dataset provided a much better match of simulated to measured vadose zone nitrate concentrations (relative to the uncalibrated version). Further calibration of soil hydraulic parameters only slightly improved vadose nitrate predictions obtained with the proper precipitation and ET dataset.

These results indicate that an important aspect of proper vadose zone modeling is to reduce the uncertainty about precipitation and ET. Only then can we expect reasonably accurate predictions of recharge rates, recharge nitrate concentrations, and travel time. Long-term, frequent (bi-weekly to monthly) water content data to 10 ft depth (here obtained with a neutron probe) proved critical for the calibration of the model, second only to measured irrigation volume, fertilizer N and harvest N data.

Key Discussion for Regulatory Agencies and the Public:

Despite the improvements in farm-scale orchard management, groundwater nitrate concentrations to date have continued to rise due to historical nitrogen loading and long travel times. Since monitoring began in 2017, the median groundwater nitrate concentration across the orchard's 20 wells has increased from 22 mg/L to 35 mg/L (Figure 1). This increase comes with a commensurable increase in salinity (to be analyzed in further detail in a follow-up project), indicating that it is less the outcome of increased N losses over the pre-HFLC period; but rather the result of increased irrigation efficiency and/or drought, already during the pre-HFLC period. Groundwater model results confirm the long-term historic increase in nitrate and suggest that concentrations will begin to decline within the next decade as the benefits of HFLC fertigation propagate downward to the water table and into first-encountered groundwater (upper 20 ft below the water table), where monitoring wells are screened. The simulations confirm that shallow monitoring well nitrate will be significantly impacted by the recharge rate, which in turn controls the travel time in the unsaturated zone (Botros et al., 2012. Figure 9).

Results also highlight the value of nitrogen mass balance tracking as a practical tool for estimating nitrate leaching at the orchard scale (Figure 6). While detailed groundwater monitoring and numerical modeling provide valuable insights, mass balance approaches offer a scalable, cost-effective method for tracking nitrogen losses and predicting groundwater trends. Integrating block-level NUE assessments, mass balance tracking, and modified fertigation strategies during orchard replanting could further reduce nitrate leaching risks.

With respect to groundwater quality control, monitoring and assessment, this study leads to three key findings:
(A) Nitrate concentrations in first-encountered groundwater across a farm are highly variable, ranging over an order of magnitude, which has implications for the design and proper application of groundwater monitoring networks.
(B) Spatially averaged nitrate concentration across the farm (orchard), at first encountered groundwater, are consistent with the NUE, i.e., with field/orchard/farm scale nitrate losses estimated from N mass balance, with proper recharge estimates.
(C) Nitrate transport in the unsaturated zone, under efficient irrigation management and in California climates / drought years with regularly less than about 1 foot (300 mm) of annual precipitation may be subject to exceedingly long (years to decades) travel time due to the small amount of recharge.

These findings provide a clearer understanding of how nitrogen management decisions impact groundwater quality. While HFLC fertigation has made measurable progress in reducing nitrate leaching, long-term improvements will require continued monitoring, adaptive management, and refinements to fertigation strategies. This work reinforces the need for practical, data-driven approaches that balance crop productivity with groundwater protection.

Finally, preliminary results indicate that managed aquifer recharge can be implemented not only without increasing nitrate concentrations in groundwater but leading to substantial long-term (multi-year) reductions in groundwater nitrate concentrations following the recharge event (here: 30 ft of recharge in one month). Results will be further evaluated to develop guidance on larger-scale application of AgMAR under various common water availability scenarios. For example, applying the results of the AgMAR study to a scenario with repeated winter AgMAR treatment showed long-term benefits to groundwater quality (Figure 10).

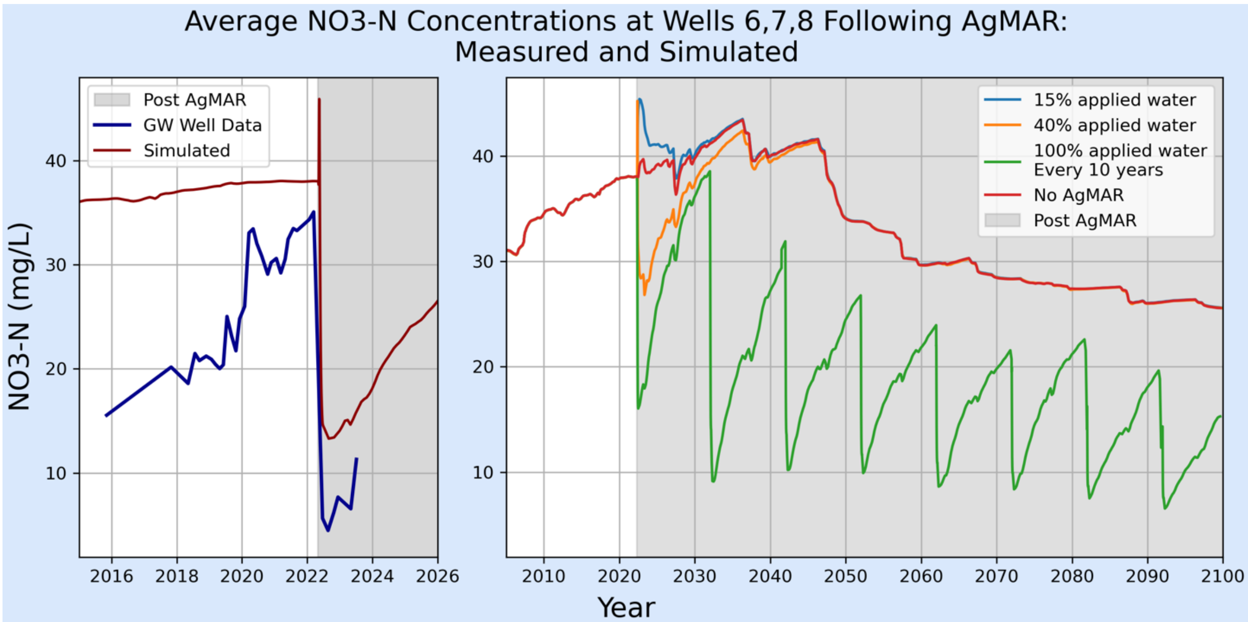

Figure 10: Scenario modeling of the AgMAR flooding that occurred at the orchard in the summer of 2022. The panel to the left shows the measured and simulated nitrate concentrations at the three wells directly below the AgMAR basins. The figure to the right shows the long-term concentrations in those wells out to the year 2100. The 15% and 40% applied water scenarios refer to applying that fraction of the amount applied in the actual experiment (10 acft/ac) across the entire orchard (1.5 ft and 4 ft). The green timeseries shows a scenario of flooding 100% of the actual applied water every ten years.

H. Challenges:

Suction lysimeters: The suction lysimeters allow for spatial sampling of pore water at various depths, which is crucial for monitoring the travel of nitrate deep into the vadose zone. However, when many locations and depths are involved, it becomes labor-intensive to install, maintain, apply vacuum, and collect samples. Additionally, given their distribution in the orchard, they are prone to damage from farm machines during harvesting. Their installation challenges often limit the depth of investigation. At the orchard farm, many of the suction lysimeters were frequently too dry during the summer and early fall to collect samples.

Tensiometers: We deployed water tensiometers with pressure transducers near the suction lysimeter stations, intending them to provide data to estimate groundwater recharge by determining water fluxes just below the root zone of the trees. Unfortunately, we were not able to consistently collect reliable data from them due to limitations in the representativeness of data from the different sensors. Some tensiometers dried out during the drier seasons. The stations require periodic cleaning as algae tends to build up in the columns over time. Like lysimeters, they are also prone to damage from farm machinery.

Vadose zone monitoring system: The VMS overcomes the challenge of investigation depth experienced with suction lysimeters as it was installed with a drilling machine. It's completely buried underground, protecting it from damage by farm machines and preventing interference with farm operations. The VMS has six sampling ports at various depths (40, 60, 240, 360, 480, and 620 cm), all easily accessible from the control box above ground. However, similar to the suction lysimeters, it still requires manual application of vacuum and sampling. It is also exceedingly expensive to install ($80,000). While it provides much larger depths of investigation than a typical lysimeter, the samples are spatially limited to the installation location and represent only one vadose zone measurement location.

Teros 12 and 21: Going forward, we will evaluate the use of Teros 12 and Teros 21 soil moisture and tension sensors in the vadose zone at various stations, which will significantly cut down on the maintenance requirements of the tensiometers and provide more reliable data. These sensors are also less prone to damage from farm machines as they can be buried underground, with data accessible via the data logger telemetry system. However, installing the sensors in a uniform soil or geological layer for consistent and comparable monitoring results is a challenge due to the heterogeneity of the orchard's vadose zone.

For all of the field work, close communication between the field monitoring team and the grower provided the foundation for successful data collection campaign, together with successful joint long-term planning of this project. Data organization and the use of a shared online data dashboard system further helped communication between project team members and the grower.

I. Project Impacts: *Use this section to describe the specific ways in which the work, findings, or products of the project have had an impact during this reporting period. Describe distinctive contributions, major accomplishments, innovations, successes, or any change in practice or behavior that has come about as a result of the project. Describe how data obtained from the project can be used and what further steps will be needed to make it applicable for growers. This section must explicitly state your project's contribution toward advancing the environmentally safe and agronomically sound use of fertilizing materials.*

- This project has successfully demonstrated the multiple benefits of the High Frequency Low Concentration (HFLC) nutrient management practice is nuts: yields have been stable or increased, fertilizer inputs have significantly decreased, and long-term groundwater quality is expected to improve by nearly 50%.
- We have provided detailed sedimentological and nitrate distribution description of the root zone, the deep unsaturated zone from 6 ft to over 20 ft and of the shallow aquifer to 40 ft depth across the 143-acre orchard farm. The results provide important, representative insights into the variability of nitrate

encountered in the subsurface across a single farm and the extent of monitoring needed to obtain results that are representative at the orchard and farm scale, informing environmental assessment and regulatory processes.

- The project has established a clear relationship between NUE and groundwater quality, aided and confirmed by vadose zone and groundwater modeling.
- Results of this project are representative of nut orchard farms across the Central Valley and provide promising management approaches for growers to comply with nitrate discharge targets set by the Central Valley Irrigated Lands Regulatory Program (ILRP).
- In collaboration with the Agricultural Water Quality Coalitions of the Central Valley, this project has become a cornerstone to the Management Practices Evaluation Program of the ILRP and aided the development of the tools used to set values and targets for nitrogen emissions to groundwater.
- The project provides timely information and guidance to growers, consultants, as well as to regulatory agencies, policy makers, and stakeholders affected by poor groundwater quality.
- Future work will evaluate young orchard management impacts to groundwater quality, assess the short- and long-term effects of agricultural managed aquifer recharge on groundwater quality following a pilot study recently implemented in the orchard.
- With successful applications for follow-up project funding by the Almond Board of California (through early 2026) and FREP (2026-2028), monitoring of groundwater, the vadose zone, and water and nutrient management practices will be continued at this site.

J. Outreach Activities Summary:

Over the project reporting period (2020-2024) and in the first half of 2025, the principal investigator and project team presented about this project or aspects of this project at 76 events, reaching an audience of 3,000 attendees (see Appendix to Section J for detailed table). This includes three presentations at the Fertilizer Research and Education Program annual conference, five presentations at the annual Almond Board Conference, and four field tours of the project orchard near Modesto. The audience included growers, grower consultants, environmental consultants, extension advisors, academics, staff members of NGOs, policy and advisory groups, and decision-makers at the regional, state, and federal levels.

Date	Activity / Presentation Title	Role	Event Organization	Event/Meeting Title	Audience	Location	Attend
2/7/2020	Sustainable Groundwater Management in Agriculture: The California Nitrate Case	Invited Speaker	Helmholtz Zentrum fur Umweltforschung UFZ	Seminar	UFZ acacdemics	Luebeck, Germany	30
4/9/2020	N Limitation in the Proposed Ag 4.0 for Salinas Valley	Presenter	Monterey County Farm Bureau	Staff and leadership meeting	Staff, ag leadership in Monterey County	COVID-19 Online	8
4/15/2020	Update on UC Davis Nitrate Modeling Work for ILRP	Presenter	Sacramento Valley and San Joaquin County Ag Coalition	Staff Meeting	Coalition leaderships	COVID-19 Online	3
4/21/2020	Overview of the NPSAT Modeling Framework and Application Context	Invited Speaker	Central Valley Regional Water Board	Staff meeting	Regulatory agency staff	COVID-19 Online	12
4/23/2020	Discussion of ILRP Nutrient Management Plan Outcomes	Participant	Central Valley Regional Water Board	Staff Meeting	Regulatory agency staff	COVID-19 online	2
5/28/2020	Sacramento Valley ILRP Ag Coalition Formula	Participant	Northern California Water Association	Technical Advising Meeting	NCWA staff, consultants	COVID-19 online	10
6/12/2020	Review of Draft Ag Order 4.0	Presenter	Sustainable Conservation	Roundtable Meeting	NGO staff, NRCS staff, RCD staff	COVID-19 online	10
6/18/2020	SWAT v HYDRUS in the MPEP Work	Presenter	Northern California Water Association	Sacramento Valley Water Quality Coalition MPEP Workgroup	Consultants, agricultural representatives	COVID-19 online	12
6/19/2020	Overview of the UC Davis Nonpoint Source Assessment Tool (NPSAT), It 's Application to the Central Valley (CV-NPSAT) and how it may fit into the MPEP	Invited Speaker	Central Valley Regional Water Board	Northern Coalitions' Phase III MPEP Work Plan and SWAT Update	Agricultural representatives , NGOs, regulatory agency personnel, consultants	COVID-19 online	30
7/14/2020	Ag Order 4.0 Pathway 2 Clarification	Participant	Central Coast Regional Water Board	Staff Meeting	RWB staff	COVID-19 online	8
8/13/2020	Using NPSAT as part of the ILRP MPEP development	Presenter	Northern Central Valley Water Quality Coalitions	Groundwater Protection Formula Briefing	Agricultural representatives , attorneys, consultants	COVID-19 online	8
9/10/2020	Nonpoint source pollution in agricultural landscapes: Assessment, monitoring, regulation, and management	Invited Speaker	Clemson University	Engineering Seminar Series	Students, faculty	COVID-19 online	25
10/28/2020	Measuring Nitrate Leaching in an Almond Orchard (co-author, presented by Hanna Ouaknin)	Presenter	**Fertilizer Research and Education Program**	**Annual Meeting**		COVID-19 online	35
12/3/2020	GNLM-SWAT Nitrate Loading and Linkage to NPSAT	Presenter	Environmental Formation	Workshop	Attorneys, consultants, agricultural representatives	COVID-19 online	16
12/14/2020	The Food-Water Link and Nonpoint Source Flux Impact on Groundwater,	Organizer	American Geophysical Union	Fall Meeting 2020	Scientists, students	COVID-19 online	100+

	Vadose Zone, and Surface Water Quality						
1/29/2021	Developing Groundwater Protection Targets with the NPSAT Simulation Platform	Presenter	Environmental Formation	Scoping Meeting 1	Consultants	COVID-19 online	12
2/5/2021	Developing Groundwater Protection Targets with the NPSAT Simulation Platform	Presenter	Environmental Formation	Scoping Meeting 2	Consultants	COVID-19 online	12
7/21/2021	NPSAT Overview	Presenter	ILRP Agricultural Coalitions	Groundwater Protection Target Small Group Briefing Series	Attorneys, agricultural representatives , consultants	COVID-19 online	20
7/26/2021	Summary of the four Central Valley CEAP Projects (N modeling, Vegetable Assessment, AgMAR, Wetlands)	Presenter	Soil Water Conservation Society	Annual Meeting, Special Session of CEAP Leaders	Academics	COVID-19 online	130
9/14/2021	Orchard Scale Modeling of Non-point Source Nitrate Groundwater Contamination in the Central Valley, California (presented by Hanni Hayes)	Presenter	Groundwater Resources Association	4th Western Groundwater Congress	Consultants, local/state/ federal agency personnel, policy makers, academics	Burbank, CA	40
10/5/2021	Using Integrated Models for Monitoring	Presenter	California Water and Environment Forum	Annual Meeting	Consultants, local/state/ federal agency personnel, policy makers, academics	COVID-19 online	60
11/3/2021	Guest Lecture: Nonpoint Source Pollution in Agricultural Landscapes: Assessment, Monitoring, Regulation, and Management	Invited Speaker	Agricultural and Environmental Chemistry Graduate Group, UC Davis	AGC 290 First Year Seminar Course	First year graduate students	Davis, CA	15
12/16/2021	Modeling the impacts of nonpoint source nitrate flux from an almond orchard on shallow groundwater in the Central Valley, California (co-author, presented by Hanni Haynes)	Presenter	American Geophysical Union	Annual Fall Meeting	Scientists	COVID-19 online / hybrid	30
9/13/2022	Quantifying long-term regional groundwater quality benefits from agricultural practices	Keynote Speaker	European Union	Land Use Water Quality 2022 Conference	Researchers, local-regional-state-federal government agency staff, consultants	Maastricht, NL	250
9/14/2022	Assessment of national or regional policy & Policies for improving water quality Plenary Session Chairs: Thomas Harter (USA) & Jenny Deaking (Ireland)	Other	European Union	Land Use Water Quality 2022 Conference	Researchers, local-regional-state-federal government agency staff, consultants	Maastricht, NL	250
9/15/2022	Increasing our understanding of 'systems function'	Other	European Union	Land Use Water Quality 2022 Conference	Researchers, local-regional-state-federal	Maastricht, NL	120

	Session Chairs: Claudia Heidecke (Germany) & Thomas Harter (USA)				government agency staff, consultants		
10/13/2022	UC Davis's Groundwater in Agriculture Program	Invited Speaker	CA&ES Dean's Office	Dean's Advisory Council	Ag and environmental leadership in industry, academia, and policy	UC Davis	40
10/25/2022	Environmental Enforcement Monitoring at the Food-Water Interface: Measuring Regulatory Land Management Performance with Comparative Integrated Hydrologic Simulations (Guest Lecture)	Presenter	UC Davis	HYD 201 A	Graduate students	UC Davis	10
10/26/2022	Orchard scale monitoring and modeling to assess impacts of nitrogen management on almond production and nitrate leaching to groundwater (presented by Hanni Haynes)	Presenter	California Department of Food and Agriculture	Fertilizer Research Education Program Annual Conference	Growers, consultants, academics, extension personnel	Visalia	80
10/27/2022	Environmental Enforcement Monitoring at the Food-Water Interface: Measuring Regulatory Land Management Performance with Comparative Integrated Hydrologic Simulations (Discussion Session)	Presenter	UC Davis	HYD 201 A	Graduate students	UC Davis	10
11/3/2022	Are Agricultural Practices Sustainable? - Assessing Long-Term Regional Groundwater Quality Benefits	Presenter	USDA Agricultural Water Center of Excellence	South West Groundwater CAP Annual Meeting	Academics, students, CAP advisory committee members	UC Davis	60
11/15/2022	Modeling the Future of Groundwater Nitrate as a Decision Support Tool	Invited Speaker	UCD Water Resources Engineering	Fall Seminar Series	Students and faculty	UC Davis	32
12/15/2022	Numerical Modeling of Efficient Nitrate Management and AgMAR Projects to Reduce Nitrate Leaching and Improve Shallow Groundwater Quality at the Orchard Scale (presented by my student Spencer Jordan)	Presenter	American Geophysical Union	Annual Meeting	Students, postdocs, researchers, faculty	Chicago	80
12/15/2022	Nitrate Validation for Non-point Source Assessment Tool in the Central Valley, California (presented by my student Zhendan Cao)	Presenter	American Geophysical Union	Annual Meeting	Students, postdocs, researchers, faculty	Chicago	80
01/03/2023	Numerical Modeling of Efficient Nitrate	Presenter	USDA W4188 Soil Physics Workgroup	Annual Meeting	Students, postdocs,	Las Vegas	50

	Management to Reduce Nitrate Leaching				researchers, faculty		
01/03/2023	AgMAR Effects on Shallow Groundwater Quality at the Orchard Scale (presented by my student Spencer Jordan)	Presenter	USDA W4188 Soil Physics Workgroup	Annual Meeting	Students, postdocs, researchers, faculty	Las Vegas	50
5/24/2023	Nitrate, pesticides, and sustainable groundwater quality management in agricultural landscapes	Invited Speaker	UCCE Ventura County	Thelma Hansen Symposium "Future of Water in Agriculture"	Consultants, engineers, local, state, and federal agency personnel, irrigation and water district personnel, attorneys, environmental stakeholders	Online	80
6/1/2023	Introduction to Groundwater Monitoring - sustainable groundwater quality management with a focus on agricultural landscapes	Invited Speaker	California Water Quality Monitoring Council	Monthly Meeting	Public, Board Members	Online	30
6/14/2023	Quantifying Long-Term Regional Groundwater Quality Benefits from Agricultural Practices	Presenter	UCOWR	Annual Meeting	Academics, students, farm advisors, NGO staff, federal agency staff	Fort Collins, CO	80
8/9/2023	Quantifying Long-Term Regional Groundwater Quality Benefits from Good Agricultural Practices	Presenter	Soil Water Conservation Society	Healthy Land, Clean Water – 78th Annual Meeting	Extension agents, academics, students	Des Moines, IA	90
8/11/2023	Water quality in AgMAR	Participant	California Department of Water Resources	Water Quality Monitoring Technical Advisory Committee	Personnel from regulatory agencies, NGOs, academia, consultancies	Online	8
12/6/2023	Continuous Fertigation and Recharge Promise Improved Groundwater Quality	Invited Speaker	Almond Board of California	The Almond Conference	Growers, agricultural consultants	Sacramento, CA	240
12/11/2023	Assessing Long-term Groundwater Quality Impacts to Guide Agricultural Policy: Linking Field Research with Basin Scale Modeling	Invited Speaker	American Geophysical Union	Annual Meeting	Scientists, students	San Francisco, CA	85
12/11/2023	The Food-Water Link and Nonpoint Source Flux Impact on Groundwater, Vadose Zone, and Surface Water Quality Poster	Organizer	American Geophysical Union	Annual Meeting	Scientists, students	San Francisco, CA	100+
12/11/2023	Quantifying Uncertainty in Evapotranspiration and Irrigation Estimates Using a Non-point Source	Presenter	American Geophysical Union	Annual Meeting	Scientists, students	San Francisco, CA	100+

	Agricultural Contaminant Transport Model and a Densely Instrumented Almond Orchard in the Central Valley, CA (presented by Spencer Jordan)						
12/11/2023	Evaluating the Performance of a Deep Vadose Zone Monitoring System using Bromide as Tracer (presented by Will Lennon)	Presenter	American Geophysical Union	Annual Meeting	Scientists, students	San Francisco, CA	100+
12/14/2023	The Impact of Vadose Zone Heterogeneity on Flow and Contaminant Transport during Agricultural Managed Aquifer Recharge: Findings from an Experimental and Modeling Study (presented by Helen Dahlke)	Presenter	American Geophysical Union	Annual Meeting	Scientists, students	San Francisco, CA	100+
1/3/2024	Field-Scale Monitoring and Modeling of Nitrate Leaching in an Almond Orchard – Update	Presenter	USDA Multistate Research Group W4188	Annual Meeting	Scientists	Las Vegas, NV	34
3/25/2024	Promoting a System-Based Approach to Advancing Agricultural Management: Role of Models as Monitoring Tools at the Food-Groundwater-Surface Water Nexus	Invited Speaker	Foundation for Food and Agriculture Research	Aligning Global Research Priorities & Investment Strategies for Sustainable Water Management	National leaders from the groundwater arena, agriculture, and watershed experts	St. Louis, MO / online	60
10/29/2024	Irrigation and Nitrogen Management, Monitoring, and Assessment to Improve Nut Production While Minimizing Nitrate Leaching to Groundwater	Invited Speaker	California Department of Food and Agriculture	Fertilizer Research & Education Program Annual Meeting	Growers, agricultural consultants, Cooperative Extension personnel	Monterey, CA	120
12/11/2024	The Food-Water-Ecosystem Nexus: Nonpoint Source Pollution Dynamics, Impacts, and Management in Groundwater and Vadose Zone Systems Poster	Organizer	American Geophysical Union	Annual Meeting	Researchers, students	Washington, D.C.	
12/11/2024	Calibration of a Vadose Zone Crop Model to Accurately Simulate Groundwater Nitrate Heterogeneity and Leaching Response to an Agricultural BMP	Presenter	American Geophysical Union	Annual Meeting	Researchers, students	Washington, D.C.	
12/11/2024	How Long Will the Groundwater Nitrate Legacy Endure in the Central Valley, California? (presented by Zhendan Cao, PhD student)	Presenter	American Geophysical Union	Annual Meeting	Researchers, students	Washington, D.C.	
12/11/2024	Assessing the effect of irrigation and fertilization	Presenter	American Geophysical Union	Annual Meeting	Researchers, students	Washington, D.C.	

	practices on nonpoint source nitrate leaching into groundwater (presented by Felix Ogunmokun, Postdoctoral Fellow)						
1/30/2025	Sustainable groundwater quality management in agricultural landscapes – the role of modeling tools	Invited Speaker	Solano County RCD	Annual Groundwater Workshop	Growers, ag consultants	Dixon, CA	52
4/15/2025	Fate of Nitrogen in the Unsaturated Zone and Groundwater at the Orchard/Farm Scale	Invited Speaker	Almond Board of California	Production Stewardship Workgroup	Growers, agricultural consultants	Modesto/online	30
4/17/2025	Groundwater Quality and Contamination: Transport Processes, Monitoring, and Sampling	Presenter	University of California Davis and UC ANR	Introduction to Groundwater, Watersheds, and Groundwater Sustainability Planning – An Online Short Course	Consultants, engineers, local, state, and federal agency personnel, irrigation and water district personnel, attorneys, environmental stakeholders	Online	150
4/17/2025	Groundwater Quality and Contamination: Transport Processes, Monitoring, and Sampling	Presenter	University of California Davis and UC ANR	Introduction to Groundwater, Watersheds, and Groundwater Sustainability Planning – An Online Short Course	Consultants, engineers, local, state, and federal agency personnel, irrigation and water district personnel, attorneys, environmental stakeholders	Online	150
5/5/2025	The UCANR Groundwater Extension Program – Role and Impact in California	Invited Speaker	College of Agricultural and Environmental Sciences	2025 College Symposium	External college stakeholders and potential funders	Davis	120
5/9/2025	Improving orchard management while protecting groundwater	Invited Speaker	Almond Board of California	ABC Environmental Stewardship Field Day at our orchard field site	Local, state, federal policy makers, EPA Region 9 leadership, state agency leaders (CDFA, SWRCB, RWBs, CDFW)	Modesto	80
5/20/2025	Monitoring and Modeling Water and Nitrate Management in an Orchard to Support a Regulatory Environment	Invited Speaker	UC ANR Cooperative Extension	Annual Walmond Tour	Farm advisors	Modesto	80
6/5/2025	Monitoring and Assessment of Nitrogen Leaching in an Irrigated	Presenter	Land Use Water Quality Conference	International Conference 2025	Academics, cooperative extension	Aarhus, Denmark	20

	Orchard Farm under Semi-Arid Climate				agents, government agency representatives		
6/18/2025	Monitoring and Assessment of Nitrogen Leaching in an Irrigated Orchard Farm under Semi-Arid Climate	Invited Speaker	Almond Board of California	ABC Production Research Summit	Growers, farm advisors, ag consultants	Modesto	400

K. References:

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Haynes, H., T. Harter, H. Dahlke, L. Foglia, 2022, Modeling Non-point Source Nitrate Groundwater Contamination at an Almond Orchard in the Central Valley, California. M.S. thesis, University of California Davis.

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Zhou, T., E. Levintal, G. Brunetti, S. Jordan, T. Harter, I. Kisekka, J. Šimunek, H.E. Dahlke, 2023. Estimating the impact of vadose zone heterogeneity on agricultural managed aquifer recharge: A combined experimental and modeling study. Water Research 247:120781, https://doi.org/10.1016/j.watres.2023.120781 (open access)

L. Appendices:

Table L1 (next page): Summary of age, acreage, N inputs and outputs, and NUE per orchard block for each study year. Assumptions for mineralization, atmospheric deposition, and denitrification are discussed in section E, objective #1. Seasons with newly replanted trees (e.g. NW block growing season 2013) were not included in calculations due to a lack of data of N uptake used to produce fruit in young trees. From 2018 – 2024, two N uptake values were obtained in each block, one based on grower reported harvest using the Brown conversion ("Brown", 68 lb N per 1000 lb almonds), and one based on grower reported harvest using manually collected samples of almond nuts, shells, hulls, and trash ("measured"). Columns "Avg. NUE" refer to acre-weighted average NUE for the entire orchard.

Orchard Block	GS	Age	Acres	N Fert. Applied	N Uptake (Brown)	N Uptake (Measured)	N for Growth	Denit-rifi-ication	N Mine-rali-zation	N Atm. Depo-sition	NUE per Block (Brown)	Avg. NUE (Brown)	NUE per Block (Mea-sured)	Avg. NUE (Mea-sured)
NE	2013	12	40	240	214	-	40	12	36	18	0.90	0.79	-	
NW	2013	1	25	-	-	-	30	-	36	18	-		-	
SW1	2013	12	25	240	183	-	40	12	36	18	0.80		-	
SW2	2013	13	25	240	197	-	40	12	36	18	0.85		-	
SE	2013	2	28	95	27	-	55	5	36	18	0.58		-	
NE	2014	13	40	257	182	-	40	13	36	18	0.76	0.77	-	
NW	2014	2	25	113	60	-	55	6	36	18	0.72		-	
SW1	2014	13	25	257	160	-	40	13	36	18	0.68		-	
SW2	2014	14	25	257	191	-	40	13	36	18	0.78		-	
SE	2014	3	28	190	140	-	65	10	36	18	0.88		-	
NE	2015	14	40	220	182	-	40	11	36	18	0.85	0.79	-	
NW	2015	3	25	161	127	-	65	8	36	18	0.93		-	
SW1	2015	14	25	220	122	-	40	11	36	18	0.63		-	
SW2	2015	15	25	220	146	-	40	11	36	18	0.72		-	
SE	2015	4	28	176	120	-	55	9	36	18	0.80		-	
NE	2016	15	40	270	158	-	40	14	36	18	0.65	0.66	-	
NW	2016	4	25	200	133	-	55	10	36	18	0.78		-	
SW1	2016	15	25	270	120	-	40	14	36	18	0.54		-	
SW2	2016	16	25	270	140	-	30	14	36	18	0.57		-	
SE	2016	5	28	200	140	-	45	10	36	18	0.77		-	
NE	2017	16	40	240	154	-	30	12	36	18	0.67	0.68	-	
NW	2017	5	25	240	196	-	45	12	36	18	0.86		-	
SW1	2017	16	25	240	128	-	30	12	36	18	0.58		-	
SW2	2017	17	25	240	143	-	30	12	36	18	0.63		-	
SE	2017	6	28	240	147	-	40	12	36	18	0.68		-	
NE	2018	17	40	190	141	147	30	10	36	18	0.74	0.83	0.76	0.83
NW	2018	6	25	238	218	238	40	12	36	18	0.92		0.99	
SW1	2018	-	25	-	-	-	-	-	36	18	-		-	
SW2	2018	18	25	190	157	149	30	10	36	18	0.81		0.77	
SE	2018	7	28	218	193	179	40	11	36	18	0.90		0.85	
NE	2019	18	40	173	103	95	30	9	36	18	0.62	0.69	0.59	0.66
NW	2019	7	25	174	111	103	40	9	36	18	0.70		0.66	
SW1	2019	0	25	55	-	-	30	3	36	18	-		-	
SW2	2019	19	25	188	116	102	30	9	36	18	0.64		0.58	
SE	2019	8	28	204	157	159	40	10	36	18	0.80		0.81	
NE	2020	19	40	175	182	170	30	9	36	18	0.96	1.02	0.91	0.95
NW	2020	8	25	210	271	232	40	11	36	18	1.22		1.07	
SW1	2020	1	25	-	-	-	-	-	36	18	-		-	
SW2	2020	20	25	190	165	149	30	10	36	18	0.84		0.77	
SE	2020	9	28	225	256	243	40	11	36	18	1.10		1.05	
NE	2021	20	40	166	134	151	30	8	36	18	0.78	0.84	0.86	0.88
NW	2021	9	25	226	210	206	40	11	36	18	0.93		0.92	
SW1	2021	2	25	70	-	-	55	4	36	18	-		-	
SW2	2021	21	25	178	135	139	30	9	36	18	0.75		0.77	
SE	2021	10	28	226	206	217	40	11	36	18	0.92		0.96	
NE	2022	0	40	68	-	-	30	3	36	18	-	0.99	-	1.00
NW	2022	10	25	201	205	194	40	10	36	18	1.00		0.96	
SW1	2022	3	25	106	115	117	65	5	36	18	1.16		1.17	
SW2	2022	22	25	144	119	125	30	7	36	18	0.79		0.82	
SE	2022	11	28	188	199	201	40	9	36	18	1.03		1.03	
NE	2023	1	40	105	-	-	30	5	36	18	-	1.05	-	1.07
NW	2023	11	25	113	160	144	30	6	36	18	1.17		1.08	
SW1	2023	4	25	113	102	115	55	6	36	18	0.97		1.05	
SW2	2023	23	25	82	66	73	30	4	36	18	0.74		0.79	
SE	2023	12	28	103	159	165	40	5	36	18	1.30		1.34	
NE	2024	2	40	83	-	-	55	4	36	18	-	1.06	-	0.99
NW	2024	12	25	156	190	169	40	8	36	18	1.13		1.03	
SW1	2024	5	25	146	134	130	45	7	36	18	0.93		0.91	
SW2	2024	24	25	43	75	71	30	2	36	18	1.10		1.06	
SE	2024	13	28	160	178	157	40	8	36	18	1.06		0.96	
Pre-HFLC (Growing Seasons 2013-2017) Average NUE:												**0.74**		-
Post-HFLC (Growing Seasons 2018-2022) Average NUE:												**0.87**		**0.86**
Post-HFLC (Growing Seasons 2018-2024) Average NUE:												**0.93**		**0.91**

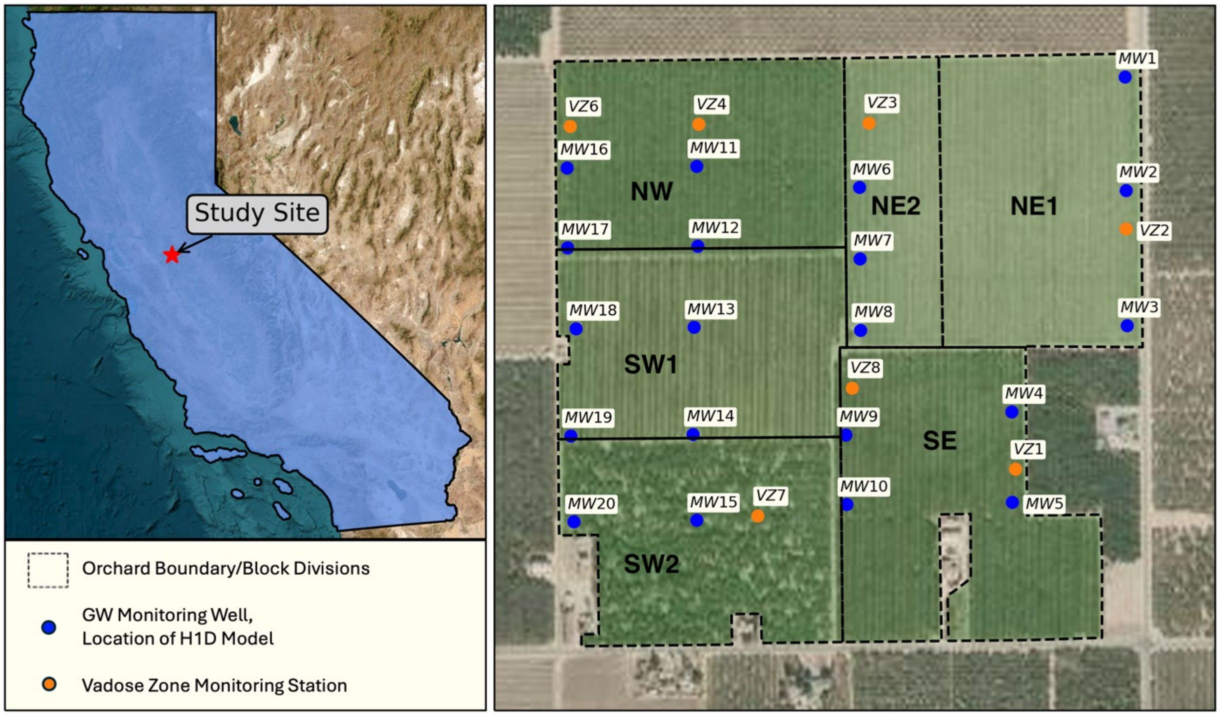

Figure L1: Study site and location of field instruments. Twenty groundwater monitoring wells (blue dots) and seven vadose zone monitoring stations (orange dots) were distributed throughout the orchard.

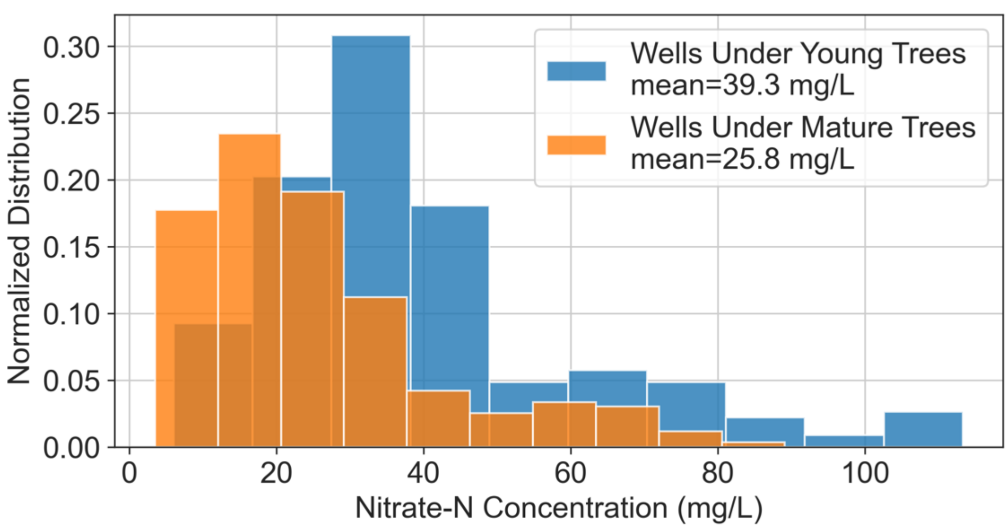

Figure L2: Histogram of measured groundwater NO_3-N concentrations under young (<5 years old) and mature trees (>5 years old). The young tree dataset includes data from wells 16, 17, and 18 following the observed replanting of the neighboring Northwest orchard in 2022.

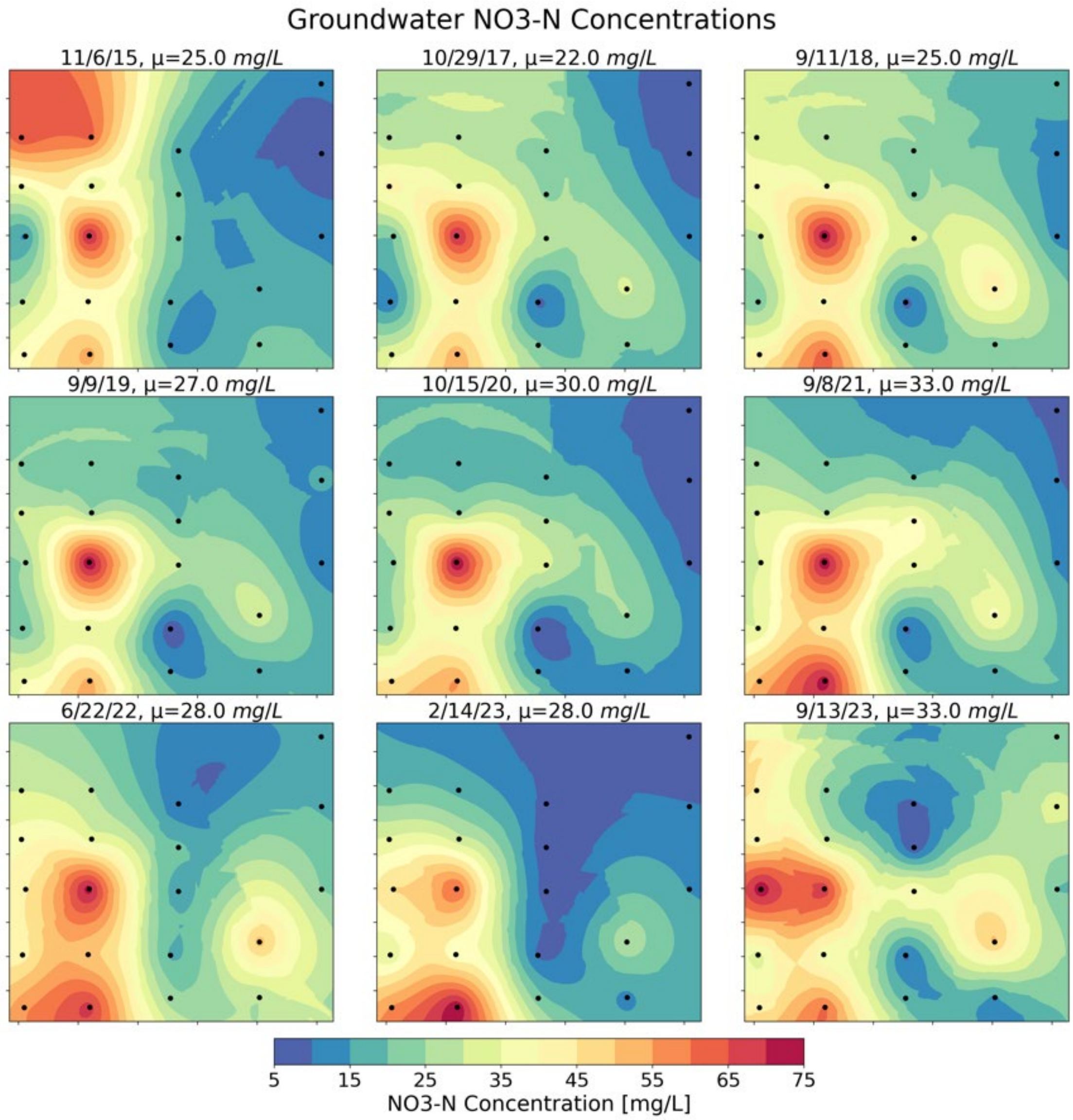

Figure L3: Spatial contours of measured groundwater concentrations through time. Higher concentrations were consistently observed in the Southwest blocks of the orchard. In the middle panel of the bottom row, the observed decrease in concentrations in the center of the orchard was a result of the AgMAR flooding that occurred in the summer of 2022.

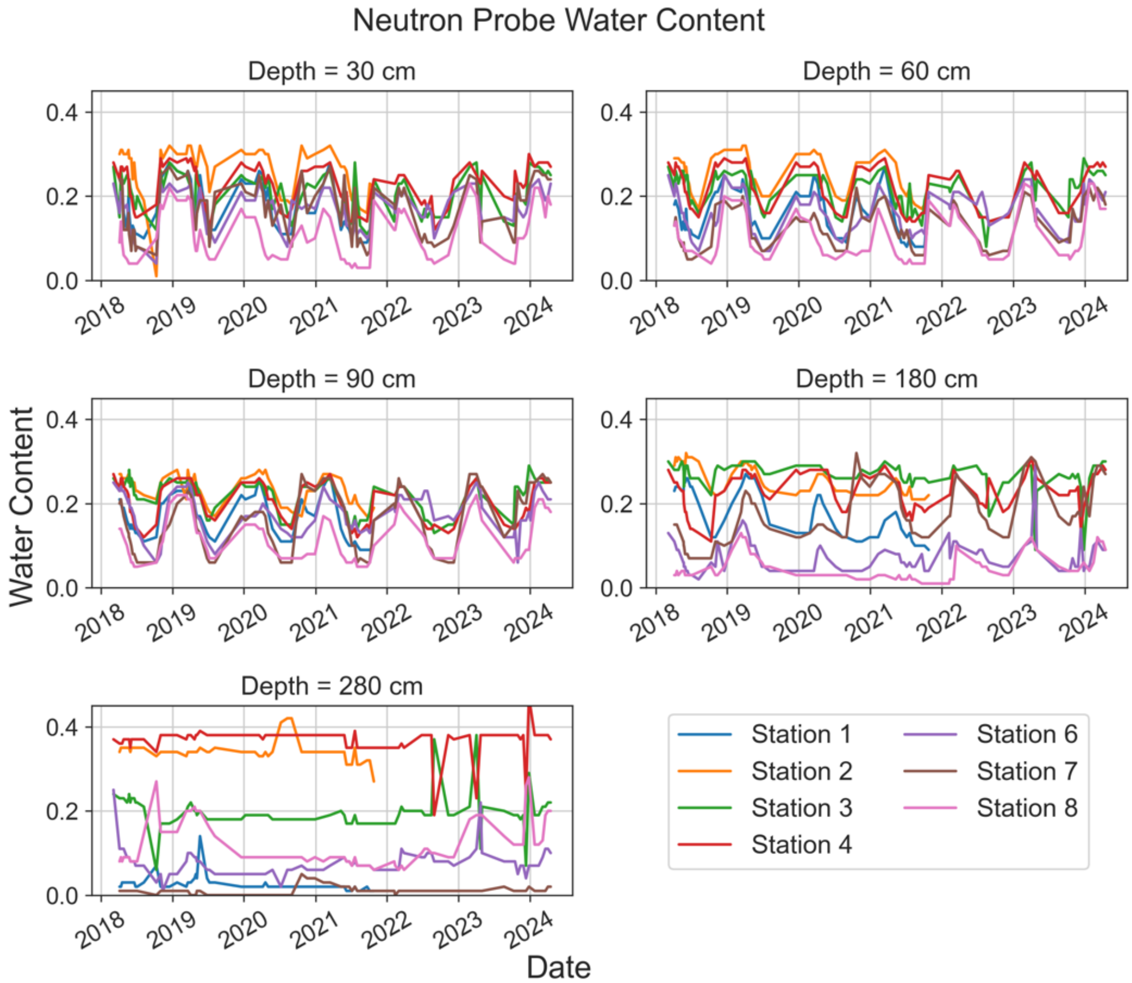

Figure L4: Neutron probe measured water content at each of the seven vadose zone monitoring stations, for each of the five available depths. Much of the variability observed at 280 cm is due to measurement noise and low data quality due.

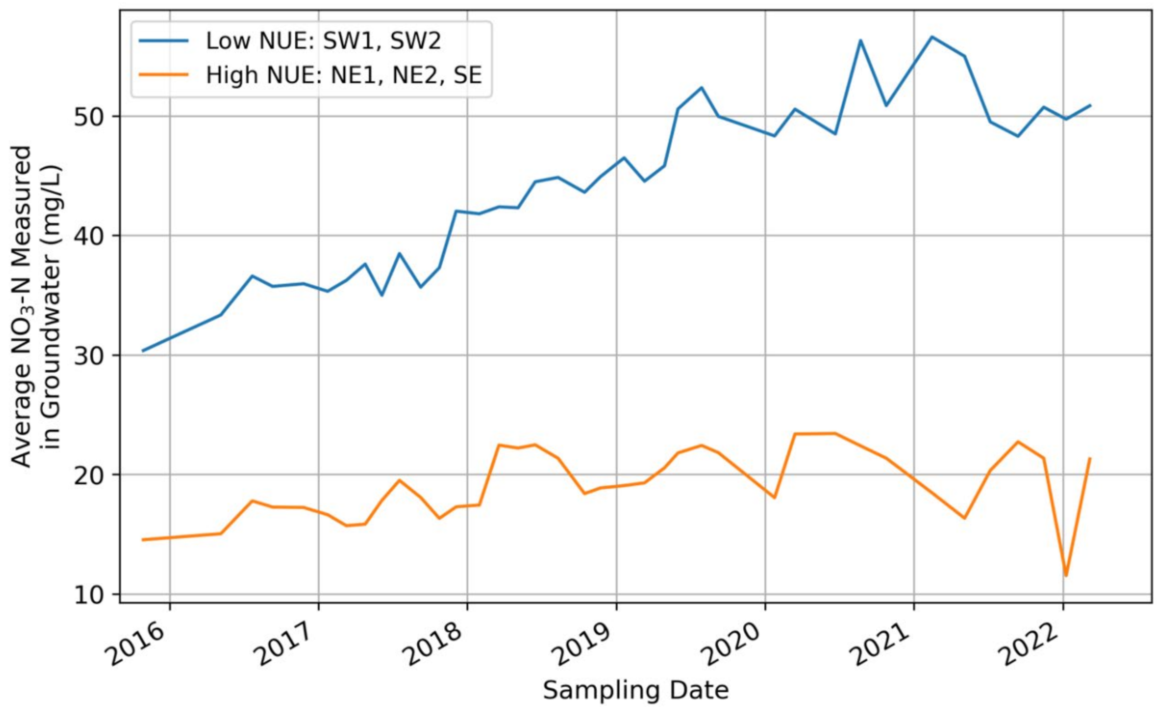

Figure L5: Average measured groundwater concentrations separated by their location in blocks which had higher average reported NUE and those with lower. A very clear trend of lower N concentrations was observed between wells sampled in low NUE areas of the orchard.

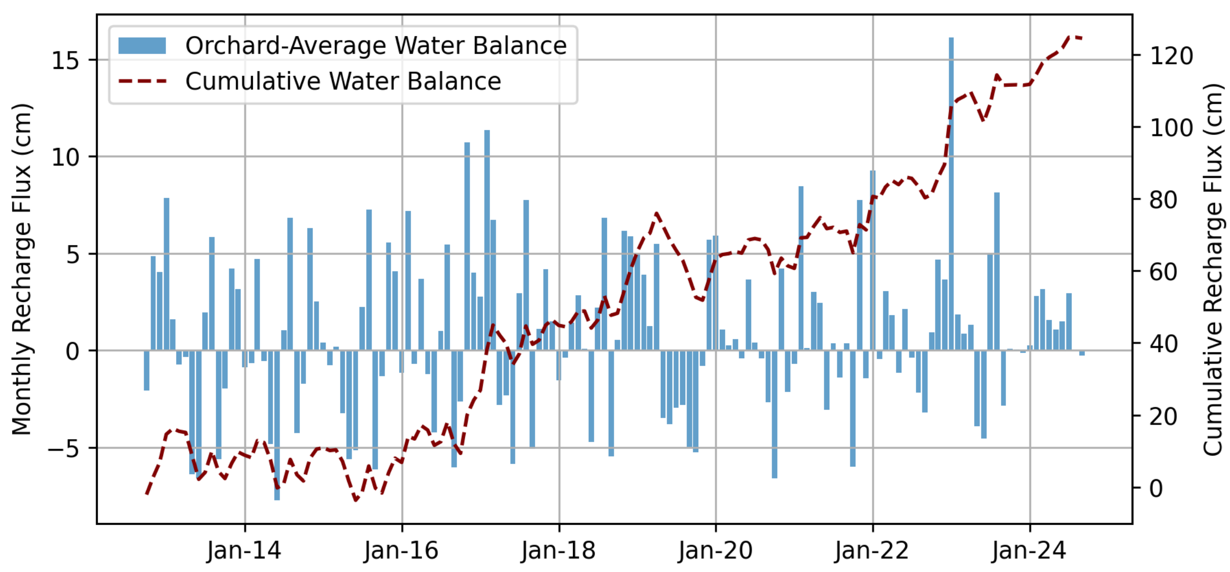

Figure L6: Simulated net change in orchard farm water balance for the entire 21 ft of the unsaturated zone, after calibration. The "water balance" is here defined as the sum of precipitation, irrigation, and evapotranspiration (negative), minus the measured change in water content. Negative changes indicated drying in the upper vadose zone. Positive changes indicate an increase in soil water content and/or recharge. Importantly, water content in the unsaturated zone in October 2013 and October 2024 is negligibly different. Hence, the cumulative change in storage is zero (and nearly zero between subsequent October samples). Therefore, the cumulative water balance over the period represents the total recharge to groundwater, with almost no recharge during drought periods, 2013-2016 and 2020-2021.

M. Factsheet/Database

Project Title

Irrigation and Nitrogen Management, Monitoring, and Assessment to Improve Nut Production While Minimizing Nitrate Leaching to Groundwater

Grant Agreement Number

CDFA Grant #19-0968

Project Leaders

Thomas Harter (UC Davis), Patrick Brown (UC Davis), Isaya Kisekka (UC Davis)

Start Year / End Year

2019 – 2024

Location

Modesto, CA

County

Stanislaus County

Highlights

- HFLC fertigation was found to increase NUE by 8% while maintaining or improving yields and required a lower average amount of N fertilizer application.
- Pore-water nitrate concentrations in the vadose zone and soil nitrogen storage in the orchard soils decreased post-HFLC.
- Vadose zone and groundwater models confirm long-term nitrate reductions, predicating a 45% decrease in N-leaching from the vadose zone in response to HFLC and observable decreases in groundwater within twenty years.
- Mass balance tracking provides a practical tool for estimating nitrate leaching.

Introduction

Groundwater contamination from nitrate leaching is a growing concern in California’s agricultural regions. In almond orchards, excess nitrogen (N) from fertilizers can move through the soil into groundwater, contributing to rising nitrate concentrations. This study evaluated High-Frequency Low-Concentration (HFLC) fertigation as a best management practice (BMP) for reducing nitrate leaching while maintaining crop productivity. Using field monitoring, nitrogen mass balance tracking, and numerical modeling, we assessed HFLC's long-term effects on nitrogen use efficiency (NUE) and groundwater quality.

Methods/Management

- **Field Monitoring:** Groundwater nitrate concentrations were measured from 20 monitoring wells across a commercial almond orchard from 2017–2024. Pore-water nitrate concentrations were collected from seven vadose zone stations biweekly.
- **Nutrient Management:** HFLC fertigation was implemented to match nitrogen supply with tree demand, reducing excess N applications.
- **Mass Balance Calculations:** Annual nitrogen fluxes, including applied fertilizer, plant uptake, and leaching losses, were tracked.
- **Vadose Zone & Groundwater Modeling:** HYDRUS1D and MODFLOW models simulated nitrogen transport and long-term groundwater quality trends.

Findings

- **Increased NUE Without Yield Loss:** After HFLC adoption in 2018, measured NUE increased from 74% to 86% (92% if 2023 and 2024 are included), and modeled NUE improved from 76% to 84%. Fertilizer applications decreased from 220 lb-N/ac/yr to 190 lb-N/ac/yr and 170 lb-N/ac/yr (first five and seven years, respectively), with no reduction in yield.
- **Decreasing Soil & Pore Water Nitrate:** Post-harvest soil nitrogen storage in the upper 60 cm decreased by 80%, from ~100 lbs-N/acre to ~20 lbs-N/acre. Vadose zone pore water nitrate concentrations also showed a downward trend.
- **Modeled Long-Term Nitrate Reductions:** Vadose zone model results showed a 45% decrease in nitrate leaching to groundwater under HFLC, and groundwater models predict nitrate concentrations will begin decreasing over the next decade as lower-nitrate recharge replaces older contamination.
- **Mass Balance as a Practical Tool:** Block-level NUE tracking and mass balance estimates correlated well with groundwater nitrate concentrations, making them a viable, cost-effective alternative for monitoring nitrogen leaching trends at the orchard scale.

This study demonstrates that HFLC fertigation is an effective BMP for improving nitrogen management and reducing nitrate leaching, but due to long vadose zone travel times, improvements in groundwater quality will take time to fully materialize. Continued monitoring, adaptive management, and targeted BMPs will be essential for further reductions in agricultural nitrate pollution.