On-Farm Flood Capture and Recharge (OFFCR) at an Organic Almond Orchard, Recharge Rates and Soil Profile Responses

Groundwater Recharge Project, 2016

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Abbreviations

CV = Central Valley
D = depth of particles displaced by water infiltration, piston flow
DIN = dissolved inorganic nitrogen
DON = dissolved organic nitrogen
EC = electrical conductivity (dS/m)
ET = evapotranspiration
Fc = field capacity, calculated from moisture probe data
N = Nitrogen
NH4-N = ammonia reported as N
NO3-N = NO3-N reported as N
TDN = total dissolved nitrogen, organic and inorganic
TDS = Total dissolved salts
VWC = volumetric water content
WR = Water recharge depth, from mass balance
Wp = wilting point, calculated from moisture probe data

Executive Summary

Groundwater in much of California's Central Valley (CV) has been critically over-drafted resulting in the implementation of the 2014 Sustainable Groundwater Management Act (SGMA). As Groundwater Sustainability Agencies (GSAs) work to comply with SGMA requirements and timelines, On-Farm Floodwater Capture and Recharge (OFFCR) is being studied to help increase recharge capacity. We implemented an OFFCR test on an organic almond orchard in the CV to assess achievable recharge rates attained through over-irrigation, and potential soil and water quality impacts. Irrigation water was applied via flood irrigation. We developed study sites and installed soil sensors for moisture and salinity monitoring, took post-irrigation deep cores to assess changes in soil and porewater nitrogen and salt concentrations through the vadose zone, and monitored agronomic practices, recharge loading and crop yields.

These studies were conducted on three recharge treatments with three replicated stations for each:

- Control at about 6 inches of flooded water to meet ET as typical for irrigation (Control treatment),
- Low Flooding of about 12 inches per irrigation application (Mid treatment),
- High Flooding of about 24 inches per irrigation application (High treatment).

Under these treatments, VWC at soil depths 6"(15 cm), 24" (60 cm) and 48" (120 cm) did not appear to reach saturation. This finding suggests equilibrium occurred between water flow downward from recharge and water flowing from the root zone through drainage, thereby avoiding a saturated condition under intermittent summertime flood irrigation. Studies at more varied locations with more varied irrigation practices would help in determining when OFFCR may lead to saturated conditions that result in anoxia conditions threatening crop health. With increasingly higher irrigation volumes, the period VWC exceeded field capacity (Fc) increased for each soil depth. For both the Mid and High treatments, Fc was exceeded at 48" (120 cm) on average 5 and 8.5 days respectively, identifying periods in which water flowed past the root zone. Drainage past the root zone did not occur under the Control treatment. Significant variability occurred at different monitoring locations, demonstrating the need to have replicated locations for assessing treatment effects on root or vadose zone conditions. On average, recharge occurred for over 9 days after an irrigation ended for the Mid treatments, and for over 13.5 days for the high treatment. In post-irrigation soil cores collected to 30' (9m) feet below ground surface, water content was lower in the shallow zone (< 5' (1.5m)), and higher and uniform with depth for all three treatments. This result was Mid treatment flushed about 75% of NO3-N (297 g/m2), 80% DON (1121 g/m2) and 38% TDS (1541 g/m2). With an estimated 2 feet of recharge from the Mid treatment, calculated average leachate concentrations were 600 mg-N/l of NO3-N, 2,255 mg-N/L of DON and 3,100 mg/L of TDS. Under the High treatment in which over 6 feet of water was recharged, 90% of NO3-N (360 g/m2) and DON (1,223 g/m2) was flushed and 62% (2,511 g/m2) of TDS was flushed. However, because more water was applied, average calculated leachate concentrations for the High treatment were lower than the Mid treatment; 220 mg-N/L for NO3-N, 798 mg-N/L for DON and 1550 mg/L for TDS. Thus, the High treatment recharge rates increase load exports by about 20% for NO3-N, 10% for DON and 60% for TDS, while decreasing leachate concentrations by 37% for NO3-N, 35% for DON and 50% for TDS (when compared to the Mid treatment). DON exports were about 4X those of NO3-N. Evidence from this study suggests constituents will not be flushed to groundwater at the same

rate and arrive at the same time. Groundwater well sampling would be helpful in better understanding potential consistent with the assumption that almond trees have relatively shallow roots and draw water from the upper soils and not the deeper soils, and recharge water moved deeper than the soil core depth. Piston flow suggests as water flows down the vadose zone, new water displaces old water and water packets move down through the vadose zone like dominos. DON peaks were found in the shallower soils for the Control treatments, but had migrated to deeper depths with recharge, higher recharge having deeper peaks. Similar findings were found for NO3-N, though the shallower peaks in the Control treatments were not found suggesting plant or microbial processing. However, some results suggest deviation from the piston flow model. Most notably, mass calculations for the Mid treatments show greater losses of mass than expected, suggesting preferential flow and preferential constituent transport. Soil profiles showed some evidence of nitrogen processing in the shallow root zone but not in the deeper vadose zone. The NO3-N to DON ratio was 0.25 in the rootzone but higher below 150 cm (0.3), and stable throughout the remaining soil core length. The lower NO3-N/DON ratio in the shallower soil indicates plant uptake or other processes have reduced the concentration of NO3-N relative to DON in the root zone, but below 150 cm those processes seem to shut down. Nitrogen and salt mass losses were calculated for the different treatments. The effects of recharge management on groundwater. Recharge did not appear to affect yields though long-term agronomic affects are uncertain.

Introduction

Groundwater makes up 38% of total water demand in the San Joaquin River hydrologic regions (DWR 2013). From 2005 to 2010, between 5.5 and 13 million acre-feet (MAF) of storage was removed from the Central Valley (CV) aquifer (DWR 2013), and San Joaquin Valley groundwater levels are more than 100 feet below previous historic lows (DWR 2014). Most climate models predict more variation in annual precipitation for CA watersheds (Reclamation 2011, 2014), likely resulting in earlier snowmelt, more precipitation as rain, increased frequency of extreme events, including droughts and floods, and earlier and more extreme runoff events (DWR 2003; Hayhoe et al. 2004; Thorne et al. 2012), challenging CA's water infrastructure to efficiently capture and convey sufficient water to meet municipal, agricultural and environmental water needs (DWR 2013).

In 2014, CA passed the Groundwater Sustainability Management Act (SGMA) in response to dropping groundwater levels exacerbated by the 5-year western drought. SGMA mandates CA achieve sustainable groundwater use. DWR identified critically overdrafted areas, including most of the CV. Those areas need to have Groundwater Sustainability Plans (GSP) in place by 2020 and to achieve groundwater sustainability by 2040, and make progress in the interim. GSPs are developed and implemented in perpetuity by locally based and self-funded Groundwater Sustainability Agencies (GSAs).

On-Farm Flood Capture and Recharge (OFFCR) is a concept in which farm lands are leveraged to capture and recharge legally and hydrologically available flood flows to increase regional capacity for recharge and replenishment of groundwater (Bachand et al, 2014; 2016). The most cited example of this approach has been recharge conducted initially under a NRCS CIG study at Terranova Ranch in 2011 (Bachand et al, 2014, 2016) and again this year (LA Times, XXXX). The Terranova Ranch project has led to the development of the first large-scale implementation of OFFCR with the McMullin Project. Under a DWR Flood Corridor Grant, the McMullin Project will enroll under Phase 1 approximately 5,000 acres (including the current project area) and have the capacity to divert 150 CFS of flood flows onto 1,500 acres actively managed for recharge during flood flow conditions. At full build-out, the project will increase the capacity to 500 CFS covering 16,000 acres of farmland with 5,000 acres managed for recharge at any given time (CNRA 2013), equivalent to 30,000 acre-feet monthly.

With OFFCR, several questions remain regarding 1) its broader applicability and ease of implementation for varied farm operations, 2) potential water quality management of groundwater water rights, 3) co-management of recharge and crop production, and 4) crop health. This project implements OFFCR on an organic almond orchard farmed with flood irrigation near Chowchilla. This project addresses the above questions to various degrees. Specifically, this project focused on the following goals:

1. Data for validation of vadose zone water quality model being developed under Specialty Crop Block Grant.
2. Vadose zone water and mass budget for quantitative data on N and salt species movement, including organic N
3. Agronomic response to farm flooding on almonds for spring period
4. Development of BMPs for flood loading to almonds

Methods

In 2016, an almond orchard in Chowchilla was used as a recharge demonstration site. This almond orchard is approximately 40 years old and has been grown under organic methods since 2014. We divided the orchard into three treatments, shown in Figure 1. On the Control treatment, the farmer irrigated as usual, targeting 6” (0.15 m) of applied water per irrigation. On the Mid treatment area, the farmer aimed to add approximately 1’ (0.3m) water per irrigation and on the High treatment area, the farmer added about 2’ (0.6m) of water per irrigation. Soil at the field is generally designated either as mapping unit GcA, (Traver loam -moderately well drained) or CaA, (Cajon loamy Sand -somewhat excessively drained) by the Natural Resources Conservation Service (Soil Survey Staff, 2017). These soil designations are generally for the top 5’ (150 cm).

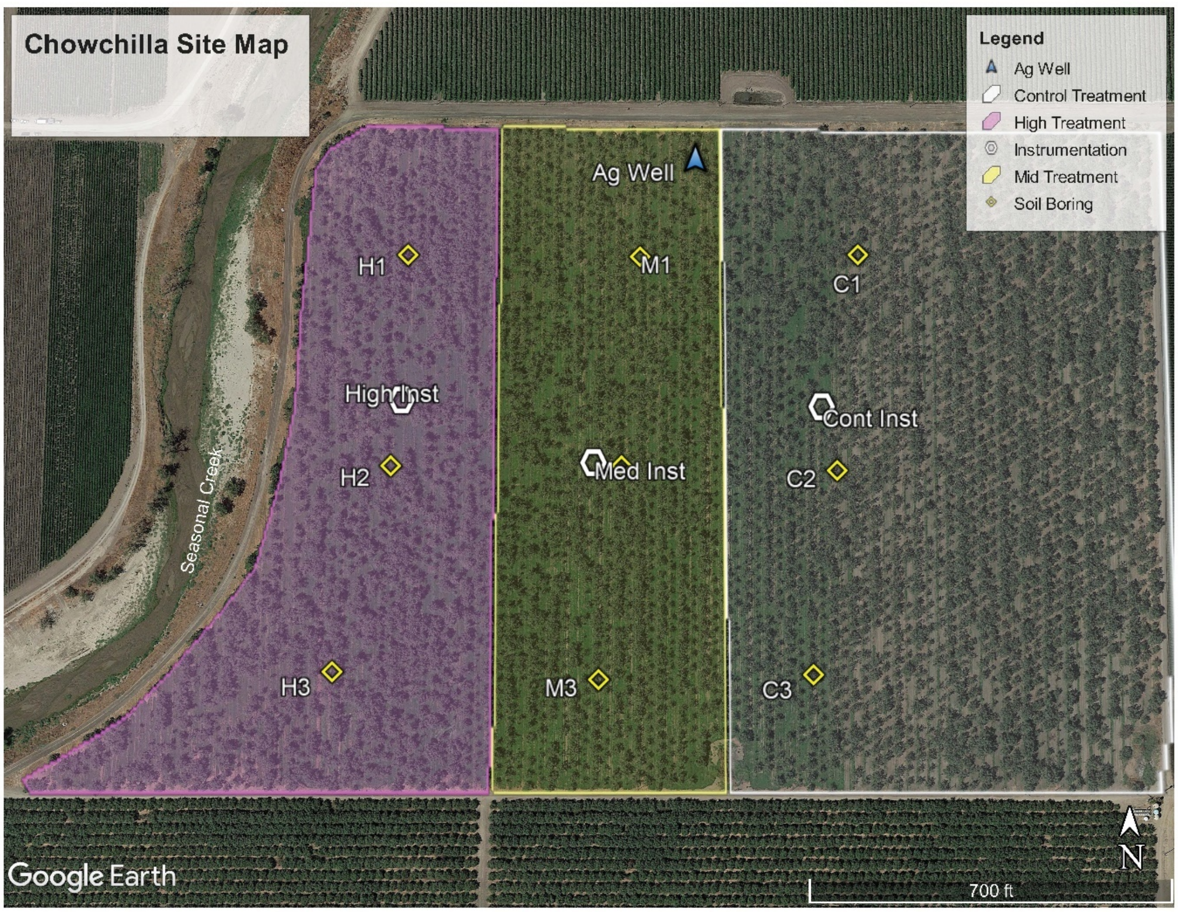

Figure 1. Chowchilla Site Map.
Figure 1 shows the orchard, treatment areas, instrumentation placement, and approximate boring locations

Irrigation and Nutrient Management

All treatments were given a standard irrigation (late April to early May) before the recharge irrigations began. Data were collected to provide information about movement of water and dissolved constituents through the vadose zone.

We tracked the irrigation application frequency and volumes using the grower's irrigation notes integrated with flow meter measurements on the main pipe carrying water to the orchard. Grower notes included date and time of the start and end of water on each treatment, and the flow rate and total volume of water from the flow meter. Irrigation was generally applied 5 to 10 rows at a time; Mid Treatment checks required about 12 hours and High treatment checks required about 1 day to complete. For the high treatment area, water was added to each check twice, with elapsed time between 1.5 and 3.5 days between stopping flow and starting flow again on any one check. Pressure transducers were installed within each treatment area to record water levels in the orchards during irrigation and recharge events. Only results for the Mid and Control treatments are available, however, because of pressure transducer failure in the High treatment.

For each irrigation event, evapotranspiration was calculated for the period between the end of the previous irrigation and the end of the irrigation event We used hourly reference evapotranspiration taken from the CIMIS data, Madera II station which is about 14 miles from the Chowchilla site. When Madera II data were unavailable or flagged unreliable, we used data from the Merced ET station (17 miles from the site). We calculated evapotranspiration (ET) based on reference evapotranspiration (ETo) as follows:

$$ET=Kc * ETo$$

Where Kc is the crop coefficient for almonds. We used Kc suggested by Doll (2010) for almonds with cover crop. Recharge per irrigation was calculated as the difference between the irrigation water applied and estimated evapotranspiration in the orchard.

The farmer managed nutrients at the orchard. Prior to the first recharge that occurred in April 2016, in March 2016, the farmer reports that he applied 5 tons of dairy manure/acre. The manure, solids from a separator, contained approximately 2.25% N by field weight based on several past tests from the same provider. The total N applied per year was therefore approximately 225 lbs/acre (25.2 g/m2). This is the usual annual rate applied to this orchard for the past 3 years, although in other years manure has been applied in the fall rather than spring. The manure was spread across the entire orchard floor. Prior to organic management, the orchard was treated with inorganic fertilizer.

Crop Production

Yield was determined by the farmer during harvest using standard practices for harvesting almonds and consistent from year to year.

Soil Monitoring using Moisture Probes

The moisture probes helped to evaluate water movement in the root zone and demonstrated how irrigation water flows through soil, filling pores that have been drained by tree roots and evaporation until soil reaches field capacity (Fc) and, if enough water is applied, flowing past the reach of roots. We installed Decagon 5TE moisture probes and In-Situ pressure transducers at each of the treatment locations in April 2016, prior to the initial standard irrigation. Moisture probe data from installation until 9/13/16 is discussed here. The instruments were used to track water and constituent movement during recharge. The moisture probes include reading of bulk electrical conductivity (EC), volumetric water content (VWC), and temperature(°C). Porewater EC was calculated as described by Hilhorst (2000) and Decagon (2016) using raw VWC, bulk EC, and temperature.

In each treatment area near the center (lengthwise; N-S), we placed the replicated moisture probes (N=3) at three depths; 6” (15 cm), 24” (60 cm), and 48” (120 cm). Each cluster was placed between tree rows, adjacent to a healthy tree. Moisture probes are installed by hand augering to the desired depth, and then pushing the probe into the bottom of the hole. The hole was augered at a 1H:2V slope, and backfilled with soil and bentonite to prevent water short-circuiting down the hole. For each installation, we collected the deepest soil from the core, and sent it to the lab for tests, including gravimetric water content and texture analyses. At each treatment area, one pressure transducer was installed next to the most “upstream” moisture probe cluster to monitor surface water depth. The pressure transducer at the High treatment failed, and was replaced by a moisture probe inserted at the surface, approximately 3” (7.5 cm) deep.

Soil Porosity Calculations

To assess soil moisture responses to flood recharge, we needed to calculate soil porosity and when it was saturated. To determine these values, we did two calculations.

First, samples of soil immediately above the moisture probes were collected and analyzed for gravimetric water content. The gravimetric water contents data were compared to VWC before the 1st irrigation, and estimates of porosity were made using relationships between volumetric water content, gravimetric water content, bulk density, and porosity.

Second, porosity was estimated from field capacity (Fc), which was determined with the moisture probes. Field capacity tends to be approximately 50% of total porosity. We were confident that at least one soil sample location reached saturation during the study: the soil monitored by a moisture probe inserted at about 3” (7.5 cm) below the surface in the High treatment. Based on the maximum VWC at that location (saturation), and the Fc at that location, we determined Fc was 59% of porosity. This relationship between Fc and total porosity (or saturation) was used for all soil for this investigation.

The final estimate of porosity was taken as the smallest of the two above calculations to be conservative in identifying periods of saturation. Maximum VWC was compared to estimated porosity to identify areas that became saturated during the study.

Determination of Wilting Point and Field Capacity

Field capacity is the soil moisture after excess water has drained and downward flow is negligible. Field capacity can be estimated by viewing VWC changes over time (Decagon, 2017). Water draining from soil can be slowed by the permeability of soil below it, especially during recharge events, and so it is sometimes difficult to clearly determine the Fc based on VWC. We found it very useful to review the drying period after the initial non-recharge irrigations because the break in the VWC is easier to determine when less water is applied. Porewater EC information (calculated from bulk EC, temperature, and soil bulk electrical permittivity) were also very useful in assigning periods of drainage because porewater EC tends to change when water is flowing through soil. Thus, we used EC combined with the VWC data to estimate field capacity. The wilting point (Wp) is reached when soil VWC is too low for extraction by plant roots. The Wp generally occurs at half Fc when the VWC in the soil is too low for the plant's roots to extract water (Decagon, 2017). When possible we estimated the wilting point as the VWC during a drying period, when VWC levels out.

Soil Cores

Soil chemistry and porewater calculations

Soil was sampled and analyzed to provide information about constituent loading in and movement through the vadose zone under the three water management treatments. Soil borings were drilled with a Geoprobe 7706 to a depth of approximately 31' (945 cm) on November 3, 2016. Soil was collected in 1.5" (3.8 cm) diameter acetate tubes while drilling, and soil was sampled from the tubes at lithological changes or at depths of 1, 2, 3, 5, 7.5, 10, 15, 20, 25, and 30 ft (30, 60, 90, 152, 286, 254, 457, 610, 762, and 914 cm). Soil was kept cold prior to delivery to Professor Helen Dahlke's laboratory at UC Davis.

Soil was analyzed for particle size distribution (texture), nitrate (NO3-N), ammonium (NH4-N), total dissolved nitrogen (TDN), electrical conductivity (EC), and total dissolved solids (TDS). Texture size determination was made using the modified pipette method, and electrical conductivity was measured using a 1:2 (soil: water) extraction volumetric; these methods are described in the Soil Survey Laboratory Methods manual (Soil Survey Staff, 1992). Extractable nitrogen species were determined in terms of N using methods outlined by Zong and Makeschin (2003), Forster (1995), Miranda et al (2001), Doane and Horwath (2003), and Wyland et al (1994). Extract TDS (mg/l) was calculated as EC (dS/m) x 640 and the was converted to porewater TDS using data on water volume added per gram soil and soil water content.

We calculated mass of constituent in the cores using soil concentrations, estimated dry density, and associated soil thickness. A constituent's concentration in soil depends on water content (and soil texture) and the constituent porewater concentration can be calculated from soil concentration. When analyzing constituent movement through soils, converting to porewater concentrations enables determination of higher concentration areas. We calculated porewater concentrations as follows:

$$\text{Concentration}_{\text{porewater, ug/l}} = (\text{Concentration}_{\text{soil, ug/g soil}}) \times (\text{Water density}, {}_{\text{1000 g/l}}) \times (\text{water content}_{\text{g water/g soil}})^{-1}$$

Prediction of Constituent and Water Movement in the Vadose Zone

The mode of constituent and water transport through the deeper vadose zone is important to constituent distribution in the vadose zone, and movement to groundwater following recharge. Flow and transport through the vadose zone has been observed as steady piston-like movement that occurs through the water-filled pores (Stevens, 1986, Bengtsson, 1987), and as preferential flow through a small fraction of saturated pores (Kung, 1990). It is difficult to predict water and constituents moving through a fingering pattern of preferential pathways. The piston flow model of flow is quantifiable, however, and will be described briefly here.

Zimmerman (1967) and Blume (1967) established that a piston flow model describes water propagation through coarse unsaturated soil, with infiltrating water displacing water in pores at the top of the profile and pushing water out at the bottom of the profile. A water or constituent particle moves through soil pores at a velocity equal to the infiltration rate divided by the volumetric water content. At the same time, the infiltrating water creates a "disturbance" or zone of increased saturation that propagates downward over time. The zone of increased saturation moves at a velocity, the celerity rate, that is much more rapid than the particle velocity. Under piston flow, constituents migrate through the soil only while the pulse of increased water saturation is passing, and the disturbance of increased saturation will move downward to the groundwater more rapidly than the individual particles.

Assuming a transport mode, we can make predictions about moisture and constituent migration after recharge, and compare those predictions to observations from soil core data. This will help us to better understand the way that transport is occurring in the vadose zone below the field site. For piston flow, we calculated the depth (d) of particles displaced by water infiltration using estimates of water recharge height (WR, from mass balance), Fc, and Wp to be as follows:

$d = WR/(Fc-Wp)$

Results

Recharge Quantities and Achievable Rates

Three recharge events occurred between the end of May and July of 2016. Table 1 summarizes these events, showing irrigation dates and times, irrigation volumes, evapotranspiration estimates, and recharge volumes. We calculated that irrigation water applied to the Control area was slightly below crop demand, a practice called deficit irrigation. Recharge for the Mid and High treatments ranged from 4 to 11 inches (11 to 27 cm) to 17 to 28 inches (42 to 70 cm), respectively. These water recharge heights likely vary across the field and could be greater at the front or back of the checks depending on field slope and other characteristics. The calculated heights are average values that likely represent mid-check conditions, where moisture probes are located. Between May and July 2016, groundwater recharge volumes achieved per event in the Mid and High treatments ranged from 5 to 12 and 19 to 31 acre-feet, respectively.

Table 1. 2016 Recharge at Chowchilla Almond Orchard

Event	Treat-ment[1]	Acres	Start Date & Time	Stop Date & Time	Irrigation Volume, ac-ft	Irrigation, inches	ET[2], inches	Recharge Inches	Recharge cm	Recharge Volume, ac-ft
1	Co	26.3	5/31/16 10:00	6/1/16 19:53	15.36	7.02	7.87	-0.85	-2.15	-1.86
2	Co	26.3	6/23/16 7:00	6/25/16 8:49	14.09	6.44	6.85	-0.41	-1.05	-0.90
3	Co	26.3	7/16/16 7:00	7/18/16 7:53	13.74	6.28	7.14	-0.86	-2.19	-1.88
							Control Total	-2.12	-5.39	-4.64
1	Mid	13.8	6/1/16 19:53	6/4/16 17:41	19.09	16.66	5.89	10.77	27.36	12.34
2	Mid	13.8	6/25/16 8:49	6/28/16 0:12	13.09	11.42	6.92	4.50	11.43	5.16
3	Mid	13.8	7/18/16 7:53	7/20/16 17:39	13.07	11.41	7.11	4.30	10.92	4.93
							Mid Total	19.57	49.71	22.43
1	High	13.5	6/4/16 17:41	6/13/16 6:06	37.29	33.15	5.64	27.50	69.86	30.94
2	High	13.5	6/28/16 0:12	7/3/16 5:53	29.14	25.90	6.24	19.66	49.93	22.11
3	High	13.5	7/20/16 17:39	7/26/16 6:05	26.5	23.56	7.05	16.51	41.93	18.57
							HighTotal	63.67	161.71	71.63
									Total Recharged (Mid and High treatments):	**94.05**

[1]Co is control, or standard irrigation, in which farmer tries to irrigate sufficiently to meet but not exceed ET demand. Mid is Medium treatment, in which farmer aimed to add approximately 1' of water per irrigation. High is High treatment, in which farmer aimed to add approximately 2' of water per irrigation

[2]ET, evapotranspiration, was calculated for each event as the sum of hourly ET that occurred between the end of the previous irrigation and the end of the irrigation event. A standard irrigation was done before these series of irrigation events. The standard irrigations ended 4/28/16 9:00 (Co), 5/13/16 12:00 (Mid), and 5/23/16 11:30 (high)

The water levels at the location of the pressure transducers, placed near the trees, were about 2 to 3 inches in both control and Mid treatments. The additional water input to the Mid treatment was accomplished by longer standing water times. Pressure transducers for the Mid treatment measured 13 to 49 hours of flooding and pressure transducers for the Control measured 11 to 22 hours of flooding. The infiltration rates were similar, ranging from 5 to 14 in/day (13 to 36 cm/day) and averaging 10 in/day (26 cm/day). Pressure transducer data was not available for the high treatment.

Root zone hydrology and salinity

The output of the moisture probe instruments shows changes in temperature, volumetric water content (VWC), and electrical conductivity (EC). Figure 2 shows an example of the VWC and EC data, for a 6” (15 cm) probe in the Mid treatment. In general, at locations where water infiltrated down to the depth of the moisture probe, results show water content rising after irrigations, and then draining after irrigation stopped. Moisture probe results for the Mid, High, and 6” (15 cm) Control locations looked similar to Figure 2. VWC in the 24” (60 cm) probes in the Control treatment showed increases with irrigation but also a general drop over time, due to deficit irrigation. The 48” (120 cm) probes in the Control showed little change in VWC or EC.

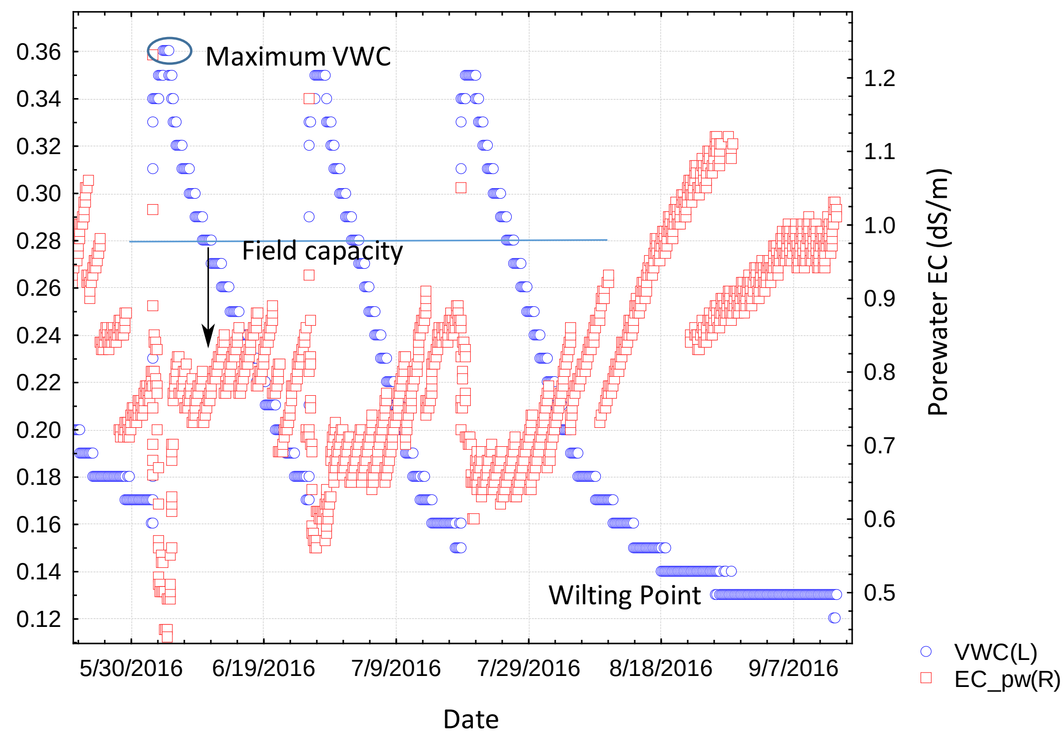

Figure 2. Moisture Probe Results of VWC and EC for 6" (15 cm) probe at Mid treatment
Figure shows moisture and EC response to the three recharge events typical for the shallow sensors. Maximum VWC, Fc and wilting point are shown. For all treatments, responses like these were shown for the shallow (6") probes. Deeper probes showed lesser effects, with response becoming less and less with depth.

Porosity, Saturation, Field Capacity and Wilting Point

We analyzed moisture probe data to identify Fc, maximum VWC and Wp and to characterize root zone hydrology in those terms. The temporal moisture and salinity trends shown in Figure 2 were used to assign changes from free draining to moisture removal by ET as described in the Methods. Recharge increases VWC to one of two conditions: 1) a level where the rate of water entering the soil equals the rate of water draining from the soil (unsaturated conductivity increases with water content) or 2) until the soil is saturated. The maximum VWC for an example location (Mid B, 6"or 15 cm) is identified on Figure 2. We calculated soil saturation as described in the Methods and summarized in Table 2. Except for the 3" (7.5 cm) location (High Treatment), measured VWC was below the estimated porosity, showing saturation was not achieved at our measurement locations and indicating the soil in general never became saturated.

This finding indicates that either 1) water is moving through preferential pathways and/or 2) soil near the surface at the Chowchilla orchard tends to have lower hydraulic conductivities than the deeper soils, so that the deeper soil can transmit the infiltrating water without reaching saturation. It is likely, especially with the second case, that saturated conditions would be found above and within lower permeability layers not able to transmit water at the rate of soil around it. However, we did not encounter this low permeability soil.

Based on a review of the curves, we believe VWC drops to the Wp several times, all after the final irrigation (Wp is identified on example graph, Figure 2). Soil reached Wp at the 6” (15 cm) and the 24” (60 cm) depths but not at the 48” (120 cm) depth. For locations where Wp was reached, the number of days required for soil to dry from Fc to Wp did not differ significantly between treatments or depths, averaging 32.6 days (SD = 4.3 days).

Table 2. Summary of moisture probe data, used to identify water movement and saturated conditions

Treatment	Rep ID	Depth (in)[6]	textural class	gravimetric moisture	VWC[0] at time of sampling	Calculated Dry Density[1] (g/cm^3)	Calculated Porosity[2]	Field capacity	Porosity based on field capacity[5]	Published Range +/- Std Dev[3]	Estimated Porosity[4]	Max observed VWC	Estimated % Saturation
Co	A	6	loamy sand	13.42	0.17	1.27	0.51	0.26	0.44	0.30-0.58	0.44	0.30	68%
Co	A	24	sandy loam	16.26	0.24	1.48	0.43	0.28	0.48	0.25-0.66	0.43	0.27	62%
Co	A	48	silt loam	21.78	0.28	1.29	0.51	0.29	0.49	0.34-0.66	0.49	0.29	59%
Co	B	6	sandy loam	12.74	0.15	1.18	0.55	0.23	0.39	0.25-0.66	0.39	0.29	74%
Co	B	24	sandy loam	14.56	0.21	1.44	0.45	0.23	0.39	0.25-0.66	0.39	0.24	61%
Co	B	48	silt loam	21.10	0.29	1.37	0.47	0.29	0.49	0.34-0.66	0.47	0.30	64%
Co	C	6	sandy loam	10.46	0.18	1.72	0.34	0.26	0.44	0.25-0.66	0.34	0.30	89%
Co	C	24	sandy loam	9.44				0.27	0.46	0.25-0.66	0.46	0.31	68%
Co	C	48	silt loam[5]	19.40						0.34-0.66	0.34	0.14	41%
Mid	A	6	loamy sand	14.29				0.27	0.46	0.30-0.58	0.46	0.31	68%
Mid	A	24	loamy sand	10.26				0.25	0.43	0.30-0.58	0.43	0.29	68%
Mid	A	48	sand	6.03				0.29	0.49	0.31-0.56	0.49	0.31	63%
Mid	B	6	sandy loam	14.72	0.15	1.02	0.61	0.28	0.48	0.25-0.66	0.48	0.36	76%
Mid	B	24	loamy sand	7.49				0.23	0.39	0.30-0.58	0.39	0.29	74%
Mid	B	48	sandy loam	11.42				0.29	0.49	0.25-0.66	0.49	0.30	61%
Mid	C	6	sandy loam	16.84	0.19	1.13	0.57	0.24	0.41	0.25-0.66	0.41	0.30	74%
Mid	C	24	sandy loam	11.51	0.19	1.65	0.37	0.23	0.39	0.25-0.66	0.37	0.27	74%
Mid	C	48	sandy loam	13.98	0.15	1.07	0.59	0.3	0.51	0.25-0.66	0.51	0.33	65%
High	A	6	sandy loam	15.25	0.13	0.85	0.67	0.28	0.48	0.25-0.66	0.48	0.33	69%
High	A	24	sandy loam	14.83				0.26	0.44	0.25-0.66	0.44	0.32	72%
High	A	48	sandy loam	9.11				0.23	0.39	0.25-0.66	0.39	0.35	90%
High	B	6	sandy loam	11.43	0.14	1.22	0.53	0.24	0.41	0.25-0.66	0.41	0.32	78%
High	B	24	loam	17.18				0.27	0.46	0.29-0.64	0.46	0.34	74%
High	B	48	loam	13.61	0.14	1.03	0.60	0.3	0.51	0.29-0.64	0.51	0.32	63%
High	C	3	loamy sand					0.25	0.43	0.30-0.58	0.43	0.43	100%
High	C	6	sand	12.97	0.12	0.93	0.64	0.22	0.37	0.31-0.56	0.37	0.33	88%
High	C	24	sandy loam	6.89				0.3	0.51	0.25-0.66	0.51	0.33	65%
High	C	48	loamy sand	4.85				0.29	0.49	0.30-0.58	0.49	0.33	67%

[0] VWC = volumetric water content; [1] Dry Density = VWC/gravimetric moisture; [2] Porosity calculated from bulk density = 1-Dry density/Specific gravity of mineral (2.6); [3] Rawls et al., 1982; [4] Porosity estimated as smallest of calculated porosity and porosiyy based on field capacity (when available); [5] Porosity calculated as (field capacity)/ (59%) because field capacity was 59% of porosity at the only known saturated location (at 3"). Field capacity is generally 50% of total porosity (Decagon, 2017) ; [6] Depths of 6", 24", and 48" correspond to approximately 15 cm, 60 cm, and 120 cm.

note: VWC, field capacity, and porosity units are m^3/m^3

Location where Saturation occurred during recharge

Depth, Period and Timing of Subsurface Water Transport

Soil moisture above Fc indicates downward water movement through the soil. For all but the 3” (7.5 cm) depth, there are three irrigations and 3 locations per treatment for a total of 9 tests.

For Mid and High treatments, surface flood water generally took 0.5 to 3 days to reach a depth of 48” (120 cm) once the flood water reached a monitoring station (Figure 3). Figure 4 plots days above Fc by depth for each treatment. Greater water applications, from the Control to the High treatments, increased the duration period above Fc (subsurface flow duration). Days above Fc increases from Control to Mid to High treatments and is generally higher at the 6” (15 cm) depth than the 24” (60 cm) or 48” (120 cm) depth. The 48” (120 cm) depth of the Control did not exceed Fc in any of the 9 tests, indicating under normal irrigation water did not travel below that depth. However, VWC exceeded Fc under 8 out of 9 Mid treatment tests and at all High treatment tests, where irrigation volume exceeded ET, indicating water flowed past the root zone.

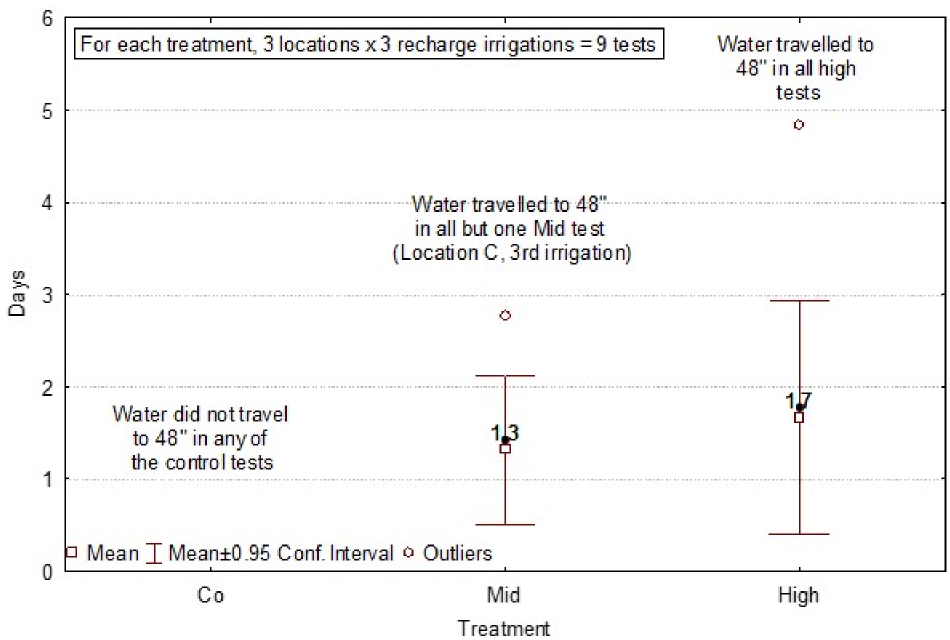

Figure 3. Time for water to travel through root zone from 6 to 48” (15 - 120 cm).
VWC above Fc defines water arrival. Under High treatments, water always flowed to the 48” (120 cm) depth. Under the Mid treatment, water flowed to the 48” (120 cm) depth in all but one treatment. Water never reached the 48” (120 cm) depth under the Control.

It is important to note, however, the variability of the results, illustrated in Figure 5 for the 48”(120 cm) depth. Results vary somewhat by irrigation because of different water quantities applied per irrigation, of the initial soil VWC before the irrigation began, and potentially from preferential flow paths. Greater variability is associated with location than with irrigation; demonstrating the heterogeneity of flow conditions in the vadose zone.

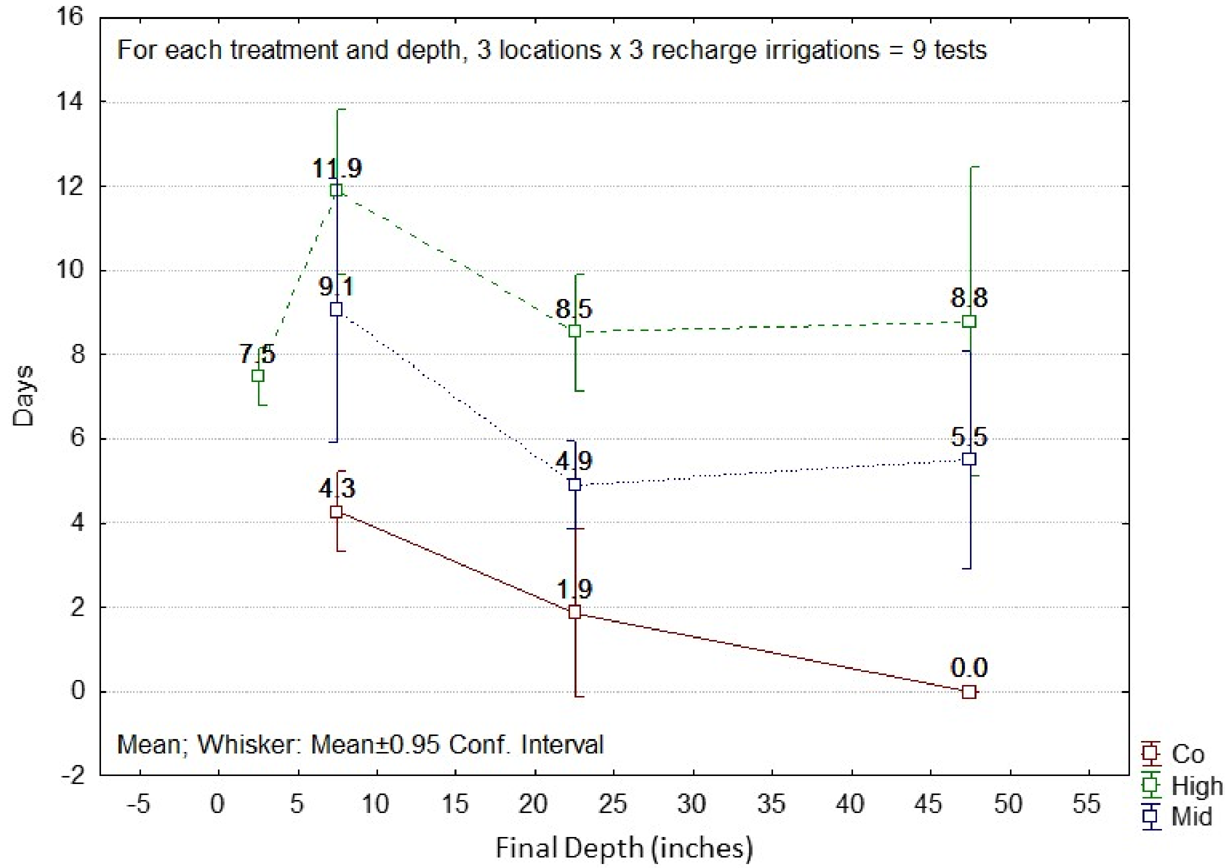

Figure 4. Longer periods of subsurface transport past the root zone with increased recharge.

The figure shows days above field capacity by depth and by treatment. Greater applications, from the Control to the High treatment increased the duration period above field capacity showing longer periods of subsurface flows with greater recharge applications. The 48” (120 cm) depth of the Control did not exceed field capacity in any of the 9 tests, indicating that water did not travel below that depth. Field capacity was exceeded at the 48” (120 cm) depth of 8 out of 9 Mid treatment tests and at all High treatment tests.

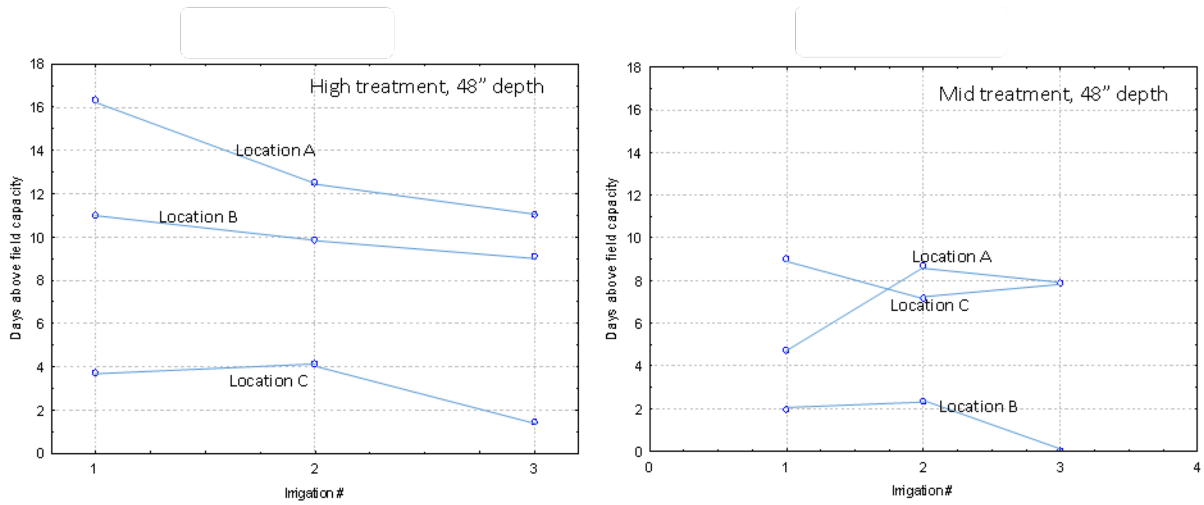

Figure 5. Variability of Moisture Probe Results
Figure shows days above field capacity at 48"(120 cm) depth for three monitoring locations by irrigation treatment. Results varied broadly between and within treatments. Locations were 25 ft (7.6 m) apart.

Electrical Conductivity (EC) changes with Recharge

Moisture probe EC results were used to identify periods of water flow as well for identifying general trends in EC. For instance, in 8 of 9 Control probes, EC either increased or stayed the same over the course of the season. In the High treatment, EC dropped over time in 4 of 6 probes placed above 48" (120 cm).

The most observable difference in EC by treatment was the response of EC to infiltration. For the Control and Mid locations, at depths where infiltration was evident, the passage of water (in two-thirds of probes) coincided with a temporary drop in EC. In contrast, water pulses in the High treatment probes were marked by an EC increase in 8 out of 9 probes (all depths included). Increased EC with water infiltration would indicate water moving through the system is carrying more constituents than are in the surrounding soil; thus, less constituent transport is occurring with infiltrating water in the Control and Mid treatments as compared to the High treatment. For illustration of how EC changes with infiltrating water, see Figure 2.

Soil core results of TDS in porewater (discussed in more detail in the following section) corroborate this finding; total dissolved solids in the porewater of High treatment samples (<48" or<120 cm deep) are statistically lower than Mid and Control treatment samples from that depth, which are not significantly different from each other. Moisture probe results are not directly relatable to lab results of EC because of the differences in methodology as well as other factors affecting soil EC besides porewater EC, such as soil density, soil structure, and the conductivity of the soil minerals.

Prediction of Constituent and Water Movement in the Vadose Zone

We analyzed flow in the vadose zone below the root zone using mass balances, and a piston flow model described in the Methods. For the Mid and High treatments, we calculated water particles and constituents moving with water would travel 15.6 ft (475 cm) and 50 ft (1,523 cm), respectively, due to the 3 recharge events.. Under piston flow, we would predict a zone of increased constituent loading (a peak) would move down the predicted distance while also spreading from hydrodynamic dispersion and/or diffusion.

In contrast, the wave of increased water saturation (the celerity) under piston flow moves at a faster rate, which is based on the infiltration rate below 48" (120 cm) (calculated per irrigation as recharge height divided by duration above field capacity at 48" (120 cm)) and the increase in VWC in the "disturbance". Using calculations described by Bengtsson (1987), we estimate that the pulse of increased saturation at either mid or high treatments would travel the 30' core depth in about 7 to 20 days and would travel 120' (3,660 cm) to groundwater in approximately four to six weeks.

By comparing soil core data to predictions based on piston flow, we can evaluate whether piston flow is describing the transport occurring in the vadose zone.

Soils and Texture

Based on the soil encountered in the first 150 cm of the borings, it seems likely the soil is most appropriately categorized as soil survey mapping unit CaA (Cajon loamy Sand -somewhat excessively drained), rather than GcA (Traver loam -moderately well drained), the other mapping unit reported at the site. The Cajon series is an alluvial soil derived from granite, with pH estimated to be about 8.7, organic measurement 0.3 to 0.8%, and $CaCO_3$ at 3%. Project soil samples collected to depths of 31' (945 cm) indicate the soil is predominantly sandy loam, interbedded with fine sand, loam, loamy fine sand, and silt loam. We encountered no clay; the mean clay content in soil was 6%, and the maximum content was 17%.

Hydrology

Texture affected water content (Figure 6). Relatively finer grained materials (loams) had significantly higher water content than coarser grained material (sands). $p<.05$). Depth also affected water content. Shallow soils down to 5' (150 cm) below ground surface had lower water contents than deeper soils, likely due to tree roots extracting water to that depth. No significant differences for water content were found by treatment. This result indicates the pulse of increased saturation caused by recharge has passed deeper than 31' (945 cm) in the 3½ months since recharge ended. This finding is consistent with piston flow calculations.

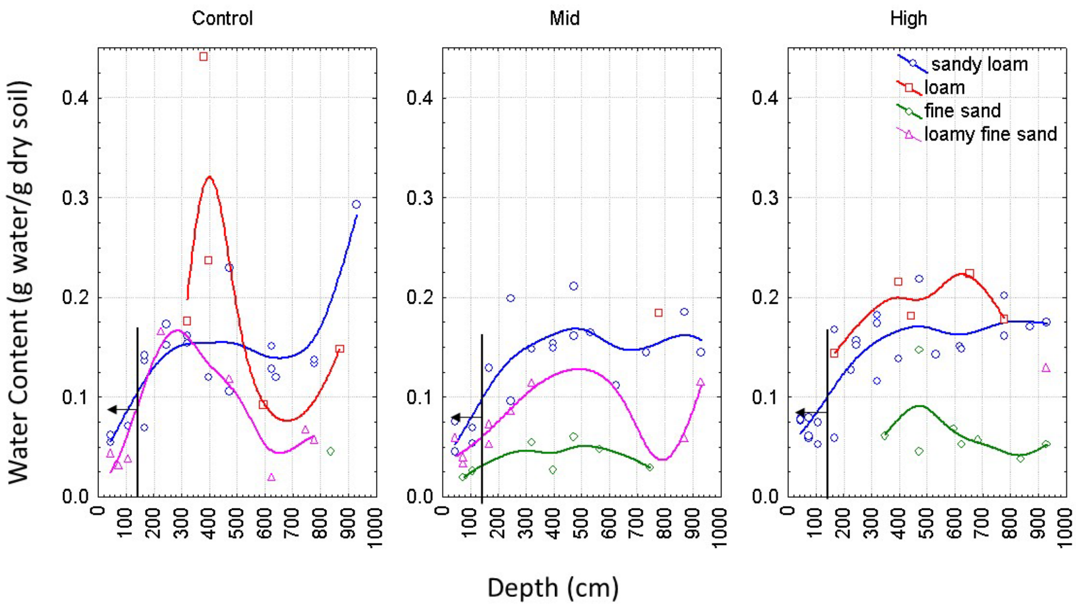

Figure 6. Water Content with Depth, Treatment, and Texture
Texture affected water content, with loams having a higher water content than sands. Water content was lower in the shallow zone (< 150 cm) and higher and uniform with depth for all treatments consistent with trees drawing water from the upper soils, not drawing upon the deeper soil profile, and recharge water moving under piston flow conditions the full depth of the soil core (and likely beyond).

Soil and Porewater Chemistry

Soil core data has been presented in several ways. We calculated analyte concentrations relative to soils and porewater. Except for NH4, the mean nitrogen species concentrations (relative to soils and to porewater) from the Control treatment are about one order of magnitude higher than for recharged Mid and High treatment samples (Table 3). About 75% of TDN was as DON, with the remaining as DIN, nearly all as nitrate (NO3-N) as compared to NH4-N. TDS levels from the Control are about twice as high than in High or Mid treatment samples. Figure 12 through Figure 15, in the Supplemental Information, show soil core data graphed by depth. Figure 7 through Figure 10 show porewater concentrations throughout the soil profile. Finally, we calculated constituent mass in the cores. Boring M1 was not used in the analyses because the boring did not extend to near 30'. All these data were used for assessing cores for constituent transport.

Table 3. Summary of Concentrations in Profiles

Mean, median, and standard deviation of NO3, DON, NH4, TDN, and TDS measured in soil samples and calculated for porewater. Samples were taken throughout the length of the core as described in the Methods.

Analyte	Treatment	N	Measured Concentrations in Soil (mg/kg)				Calculated Concentrations in Porewater (mg/l)			
			Mean	Median	Range	S.Dev.	Mean	Median	Range	S.Dev.
NO3-N	Co	34	26.3	26.5	0.1 - 84	23.6	187	204	2 - 594	127
	Mid	34	5.6	3.5	0.1 - 21	5.4	58	56	2 - 202	51
	High	40	2.0	0.1	0.1 - 23	5.2	15	2	1 - 144	35
DON-N	Co	34	93.4	92.8	1.0 - 268	68.8	786	761	19 - 2373	549
	Mid	34	13.5	0.7	0.0 - 102	24.4	130	11	0 - 1008	235
	High	40	8.0	0.0	0.0 - 86	18.9	68	0	0 - 567	150
NH4-N	Co	34	0.29	0.13	0.08 - 2.7	0.52	4	1	0 - 50	10
	Mid	34	0.21	0.13	0.05 - 1.6	0.26	3	2	1 - 27	5
	High	40	0.19	0.12	0.06 - 0.9	0.18	2	1	0 - 12	3
TDN-N	Co	34	120.1	118.3	1.2 - 352	91.3	977	992	30 - 2594	638
	Mid	34	19.1	4.7	0.1 - 123	28.5	189	65	2 - 1098	265
	High	40	9.9	0.1	0.1 - 108	23.4	83	2	1 - 713	174
TDS	Co	34	295	290	1 - 876	205	2585	2277	9 - 6757	1506
	Mid	34	169	143	2 - 472	115	2150	1583	33 - 8727	1810
	High	40	104	90	22 - 281	63	877	813	294 - 1820	390

Table 4. Estimated Mass and Mass Removal

For each core, the mass in each core, the average mass by treatment, the change in mass due to recharge, and the % removed by recharge was calculated for each constituent.

	Average Mass within Core, to 945 cm (31'), g/m2				
Treatment[1]	NO3 - N	NH4 - N	TDN - N	DON - N	TDS
Core	Mass within Core (945 cm), grams				
C1	462	3.2	2104	1639	4779
C2	345	2.6	1416	1081	3185
C3	408	3.8	1857	1445	4250
M2	92	3.3	365	273	2101
M3	122	1.7	385	263	2960
H1	120	2.7	533	415	2495
H2	5	2.4	78	72	1022
H3	10	1.9	12	3	1164
Treatment[1]	Average Mass within Core to 945 cm (31'), g/m2				
Control	405	3.2	1792	1389	4071
Mid	107	2.5	375	268	2531
High	45	2.3	208	163	1561
Treatment[1]	Change in Mass due to Recharge, g/m2				
Mid	297	0.7	1417	1121	1541
High	360	0.9	1584	1225	2511
Treatment[1]	% Mass Removed due to Recharge				
Mid	73.5%	23.1%	79.1%	80.7%	37.8%
High	88.9%	27.2%	88.4%	88.2%	61.7%

Notes:

[1]The control treatment was supplied with water approximately equal to ET demand. For the Mid treatment, water was applied over ET demands on three occasions, for a total of 19.6 inches (49.7 cm) water recharge. For the High treatment, water was applied over ET demands on three occasions, for a total of 63.7 inches (161.7 cm) water recharge.

2 Mass within the cores was calculated for 31' depth (945 cm). Mass within core M1 was not calculated because the core did not extend beyond 15', where drilling was stopped by dense very fine sand

NO3-N

Figure 7 shows variability in NO3-N concentration within the cores, but also indicates peaks of NO3-N porewater concentrations have migrated downward with increased recharge. Two of the three Control cores show porewater NO3-N peaks, one at 150 cm and one at 350 cm, while one Control core shows NO3-N increasing through the core. Two of three Mid treatment cores show a NO3-N concentration peak approximately 400 to 600 cm. Two of the three High treatment cores have very little NO3-N left at any depth in the profile and one High treatment core shows a peak at about 700 cm. Nitrate porewater concentrations are relatively low in recharged treatments (above the migrated peaks) and relative to the corresponding depths in the Control.

The calculated average mass of NO3-N in the cores, are 405, 107, and 45 grams/m2 for the Control, Mid and High treatments, respectively, indicating average NO3-N removed from cores due to recharge is 74% and 89% for Mid and High treatments, respectively. Considering recharge of 19.6” (49.7 cm,497 liter/m2) in the Mid treatment and 63.7” (161.7 cm, 1617 l/m2) in the High treatment, we estimate the average NO3-N concentration of water leaching below 31’ (945 cm) to be 598 mg-N/l (Mid) and 222 mg-N/l (High).

The average mass of NO3-N in the Control cores is equivalent to 3,616 N-lb/ac (405 g/m2). If all of this NO3-N was added by fertilization, that would be the equivalent of adding 36 lb/acre/year (4 g/m2) above plant needs for 100 years. Agriculture with irrigation began in the late 1880s, using artesian wells (Chowchilla Water District, 2017). Besides fertilizer, NO3-N can originate from plant and animal decomposition, and from cover crops. Also, nitrogen in the soil may be a remnant of the declining groundwater table; the nitrate concentration in the groundwater at the time would have been left in soil pores. These other sources may have contributed to NO3-N observed in the soil profile. The amount of NO3-N measured for this study is higher than what was measured by Waterhouse (2016) in her analyses of soil cores below 4 conventional almond orchards. She found between 330 and 1,418 NO3-N lb/acre (37 and 159 g/m2) in the top 9m (30 ft). The relatively high levels of NO3-N may be partially attributed to adding manure 1 month before recharge, which may not have been enough time for the trees to uptake the nutrients.

Dissolved Organic Nitrogen

Porewater DON distributions are like porewater NO3-N patterns for the cores in the recharged Mid and High treatments, indicating similar transport mechanisms (Figure 8). However, DON concentrations are highest in the root zone of two of three Control cores, whereas NO3-N does not peak similarly in the root zone in any core. This result indicates NO3-N removal by trees or other surficial processes, but similar DON removal is not observed.

In Control cores, we found porewater NO3-N significantly related to DON in porewater, where DON concentrations were less than 1,000 mg/l. NO3-N was 0.25 times DON in the rootzone above 5’ (150 cm) with r2=0.92 and 0.3 times DON (r2=0.86) greater than 5’ (150 cm). The lower NO3-N/DON ratio in the shallower soil indicates plant uptake or other processes have reduced the concentration of NO3-N relative to DON in the root zone. At depths greater than 5’ (150 cm), the NO3/DON ratio does not change significantly with further depth in the vadose zone, suggesting mineralization or denitrification is not continuing to occur deeper in the vadose zone. Low NH4 concentrations deeper in the vadose zone also suggest that mineralization is probably not happening.

The calculated average mass of DON in the cores are 1,389, 268, and 163 grams/m2 for the Control, Mid, and High treatments, respectively. When compared to the Control cores, DON removal from cores due to recharge is 81% for the Mid treatment and 88% for High treatments. We calculate the average DON concentration of water leaching below 30’ is 2,255 mg-N/l and 758 mg-N/l for Mid and High treatments, respectively. These levels are three to four times what was found for NO3-N and are much higher than what can be expected from 3 years of manure applications (total N applied with manure estimated to be 25 g/m2/yr so 75 g/m2 total). However, the relatively high levels of DON may be partially attributed to adding manure 1 month before recharge, which may not have been enough time for the trees to uptake the nutrients.

NH4-N

Like DON, NH4-N porewater concentrations (Figure 9) tend to be highest in the root zone (above 5' or 150 cm), where the average porewater NH4-N concentration is 17, 8, and 6 mg/l, in the Control, Mid, and High treatments, respectively. Ammonium concentrations below the root zone average 1.2 mg/l for all treatments. The presence of NH4 with DON near the surface may show that mineralization is occurring at that depth. Unlike DON, NH4-N drops to a relatively constant level below the root zone, indicating mineralization is not occurring and, by the time NH4 has travelled below 150 cm, nitrification has converted NH4-N to nitrites and then NO3-N (nitrites not measured). The mass of NH4-N in the cores is low compared to other constituents, with an average of 3.2 NH4-N g/m2 in the Control and 2.5 and 2.3 NH4-N g/m2 in the Mid and High treatments. An average of 23% of NH4 is removed in the Mid treatment and about 27% of NH4-N is removed in the High treatment.

TDS

TDS concentrations vs depth in porewater Is shown on Figure 10. TDS is a measurement of the concentration of ions and can include NO3-N, sulfate, chloride, and more, even soil organic matter such as humic/fluvic acids (WHO, 2003), and were estimated for this project using EC measurements of soil extracts. At this site, TDS is approximately one order of magnitude higher than the NO3-N in porewater and is also higher than DON concentrations. TDS were not flushed from the profile as readily as the nitrogen species that we studied. It is possible that there is a higher residual concentration of TDS, with more TDS related ions, relative to NO3-N or DON, held within pores not water-filled during recharge. On average, 1,541 g/m2 (55%) and 2,511 g/m2 (62% of TDS) were flushed for the Mid and High treatments, respectively. The average TDS concentration of water infiltrating below 30' was about 3,100 mg/l for the Mid treatment and 1,550 mg/l for the High treatment.

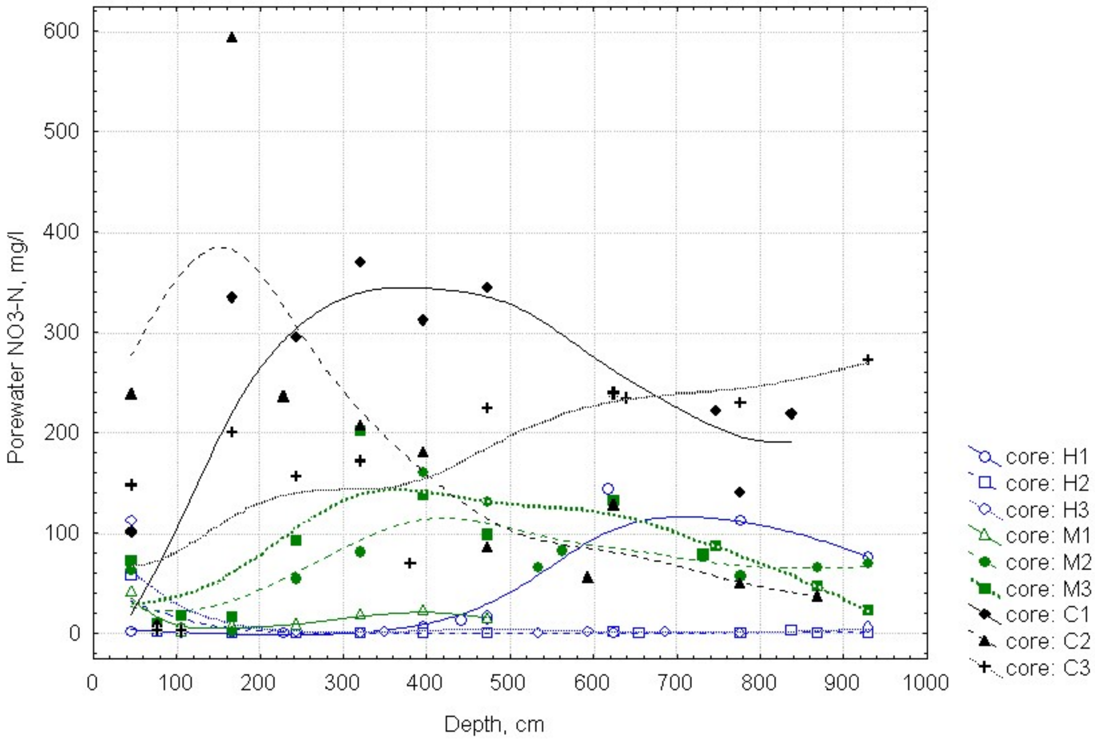

Figure 7. NO3-N Concentrations in porewater (mg/l)

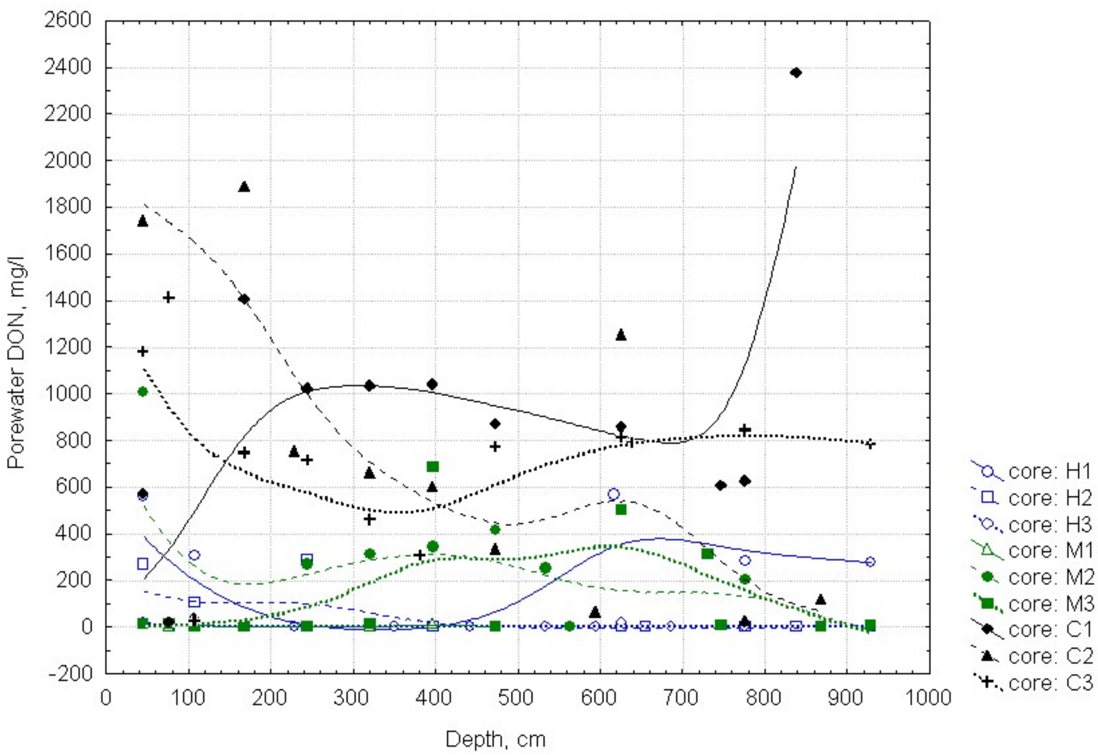

Figure 8. Dissolved Organic Nitrogen (DON) Concentrations in porewater (mg/l)

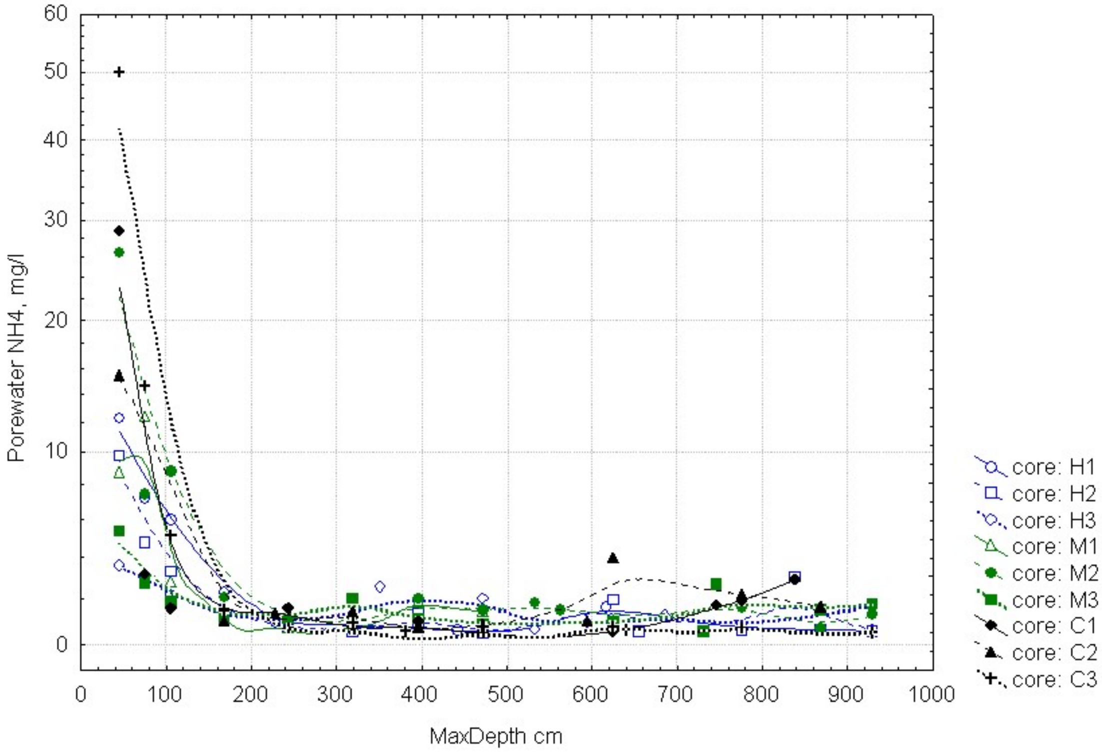

Figure 9. Ammonium (NH4-N) Concentrations in porewater (mg/l)

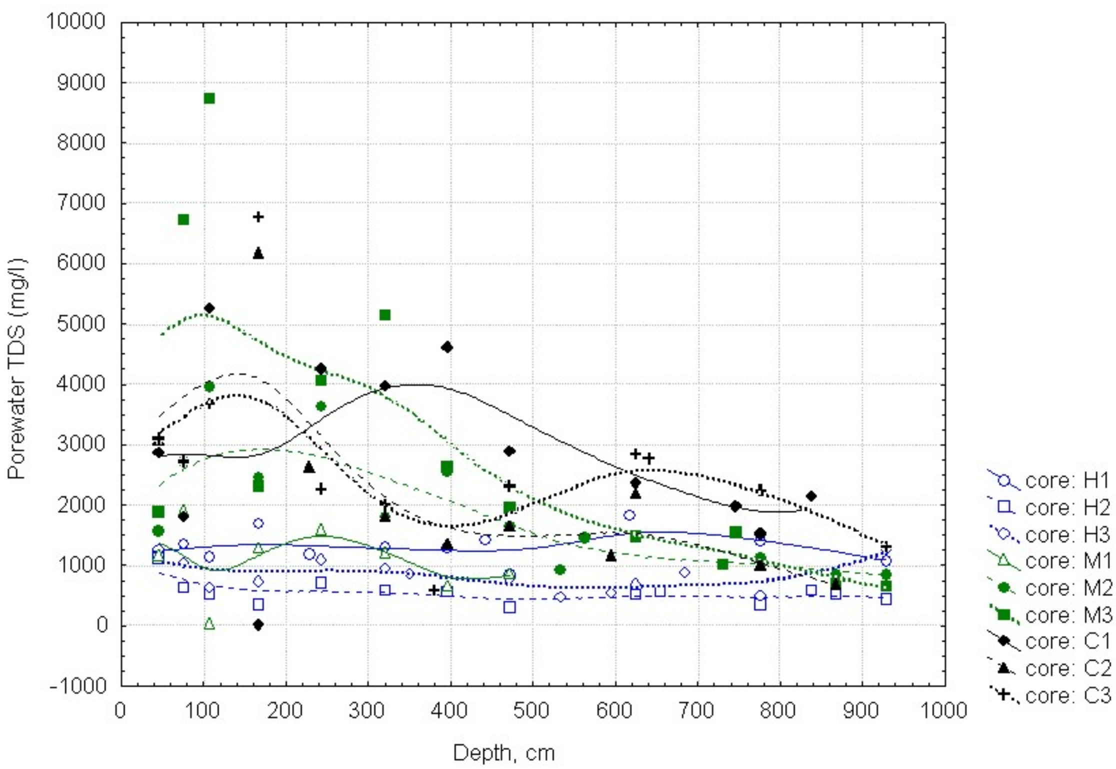

Figure 10. Total Dissolved Salts (TDS) Concentrations in Porewater (mg/l)

Potential Effects of Recharge on Yield and Tree fall at Chowchilla

At a site visit on June 22, 2016, several fallen trees were counted within each treatment area. The tree fall numbers (Table 5) indicate that the one recharge irrigation that had occurred June 22nd may have caused trees to fall. The farmer believes the tree fall is normal and that the variability is consistent with what he has seen in the past. However, these observations indicate that tree-fall should be considered in future recharge studies.

Because of differences in orchard quality between the west (High Treatment) and east side (Control), the farmer felt comparison of yield by treatment would not be meaningful. Instead, he provided 5 years of yield data to compare to 2016 yields. The yields have been dropping in 40-yr old orchard over these years (Figure 11) and although the 2016 yield number seems quite low, it appears to simply be continuing a general trend (r2=0.96), indicating that the low yield is likely not related to the recharge irrigations. Because of increased problems and reduced yields in older orchards, the University of California Cooperative Extension (2016) estimates life of an almond orchard at 23 years and so the declining yields observed at this site are expected..

Table 5. Tree Fall Observations, 6/22/2016

Treatment	# trees down	Area	#trees/area
Co	5	26.25	0.2
Mid	5	13.75	0.4
High	8	13.5	0.6
Total Area	18	53.5	0.3

Note: Acording to the grower, the number of tree fall is normal for this orchard and differences between treatments are within the range of variabiity that he has observed in the past, with trees less healthy on the west side (high treatment) than on the east side (control treatment) of the orchard.

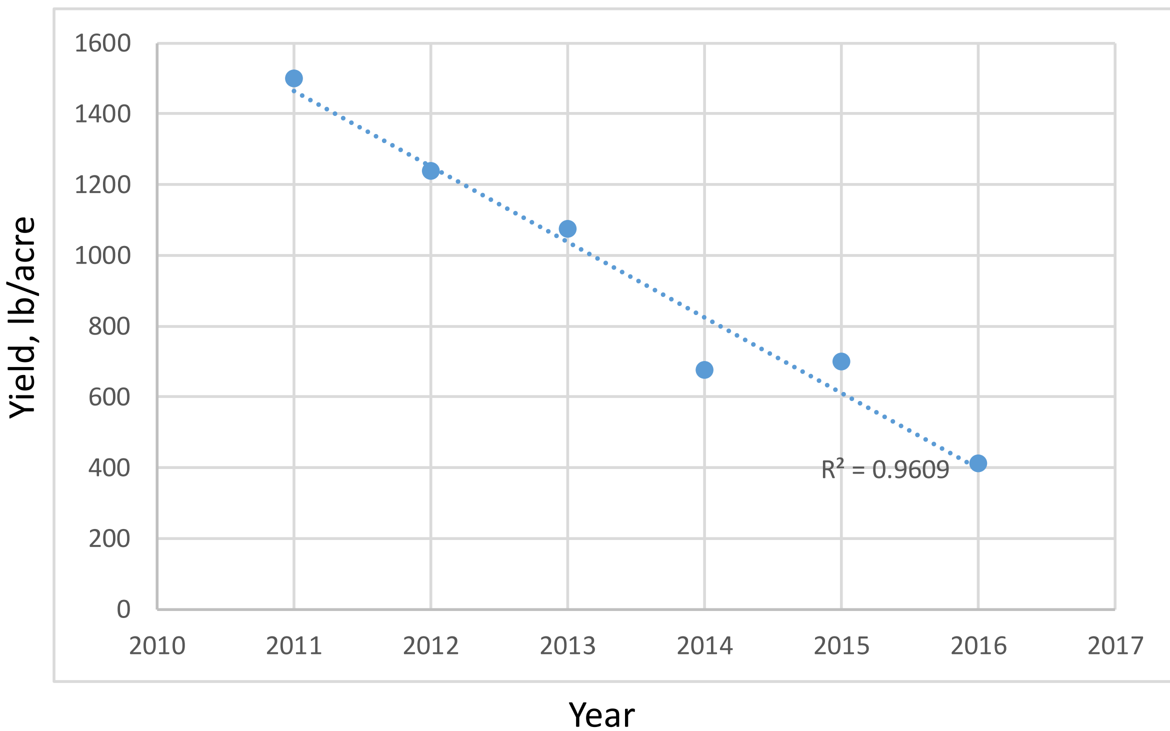

Figure 11. Yields over time at Chowchilla Almond Orchard
Yields have been dropping in this old orchard over these years. 2016 yields are in line with yield trends in this old orchard.

Discussion

Duration of Saturation During Recharge

It is important to understand moisture conditions during recharge because saturated soil may not be healthy for almond trees. The FAO reports that saturated soil conditions for more than 2-5 days can be detrimental to plant growth. Under saturated conditions, oxygen is not available for plant uptake. A water budget occurs in the root zone with water entering through irrigation and exiting through drainage. If water application rates exceed drainage rates, then soils would be expected to become saturated, and eventually surface ponding or soil saturation would occur. At this site though, drainage rates appeared to exceed application rates after soils reached Fc. In this study, VWC reached saturation only at the one 3" (7.5 cm) deep monitoring location and remained unsaturated at all other locations. The saturation duration at 3" is likely directly related to the presence of ponded wateron the field; the sensor indicated saturation for a total of 1 to 2 days per irrigation. Table 2 shows maximum % saturation at all locations. These data show that summer recharge using intermittent flooding on well drained soils does not necessarily result in saturation and anoxia in the root zone. Factors affecting vadose zone hydrology and the potential for saturation include depth to the least permeable soil. Assuming water will pond above lowest permeability layers, if those layers are present at the top of the soil profile, the rootzone below may remain unsaturated. This is apparently what occurred at this site. Alternatively, if the lowest permeability layers are deeper within the root zone, soil above that layer may become saturated during recharge events. Since non-aquatic plants get oxygen from the air spaces in the soil, saturated conditions stop plant roots from obtaining sufficient oxygen to keep healthy and perform their role of taking air, water, and nutrients from the soil into the plant (Raven et. al., 1999). More work in this area is needed to help determine management practices for OFFCR that will minimize potential for crop health issues related to recharge.

Non-Ideal Piston Flow Transport in the Vadose Zone

Observations of NO3-N and DON concentrations in the cores (Figure 7, Figure 8) suggest piston flow transport. DON concentrations are highest in the root zone of two of three Control cores, with deeper peaks for the recharge treatments. NO3-N shows similar trends as well. Two of the three Control cores show porewater NO3-N peaks, one at 5' (150 cm) and one at 11.5' (350 cm), while one Control core shows NO3-N increasing through the core. Two of three Mid treatment cores show a NO3-N concentration peak approximately 13' to 19.7' (400 to 600 cm). Two of the three High treatment cores have very little NO3-N left at any depth in the profile and one High treatment core shows a peak at about 700 cm. Also in the recharge treatments, nitrate porewater concentrations are low both above the migrated peaks and relative to the corresponding depths in the Control. These observations are consistent with piston flow. Recharge water pushes existing porewater down through the profile, transferring the NO3-N deeper and causing low porewater concentrations of NO3-N in soil above the recharge front. The depths of the NO3-N peaks are also consistent with piston flow calculations.

However, the data suggest that more rapid flow than direct piston flow and transport is occurring. With piston flow, we expect if porewater NO3-N peaks observed in the Controls were pushed down in recharge plots, NO3-N peaks may spread out due to dispersion and diffusion, but the mass of the NO3-N peak would remain unchanged. However, in M3 (Mid Treatment 3), where the NO3-N peak seems largely contained within the core depth, the peak mass is much smaller than that of NO3-N peaks in the Control cores (Figure 7). The mass of NO3-N estimated in M3 is 122 g/m2 (compared to 345 to 462 g/m2 observed in the Control cores, Table 4), or about 30% of the Control average. Thus, it appears a significant portion of the NO3-N has migrated below the observed NO3-N peak and below the end of the core. This NO3-N loss suggests preferential flows, water flowing more rapidly in some pores than others. We do not know how far through the vadose zone NO3-N travels below the core depth.

Microbial Processes

In Control (non-recharged) cores, we found porewater NO3-N significantly related to DON in porewater, where DON concentrations were less than 1,000 mg/l. NO3-N was 0.25 times DON in the rootzone above 5' (150 cm, r2=0.92) and 0.3 times DON (r2=0.86) below 5' (150 cm). The lower NO3-N/DON ratio in the shallower soil indicates plant uptake or other processes have reduced the concentration of NO3-N relative to DON in the root zone. Below 5' (150 cm), the NO3/DON ratio does not change significantly with further depth in the vadose zone, suggesting mineralization or denitrification is not continuing to occur deeper in the vadose zone. Low NH4 concentrations deeper in the vadose zone also suggest that mineralization is probably not happening.

Loading and Leachates from Recharge and Organic farming considerations

Mass losses below 30' (9m) were calculated from recharge. For this farm, DON concentrations were about 4 – 5X higher than DIN concentrations (Table 3). Thus, mass flushing of N species was primarily from DON. Salts also were flushed. The Mid treatment flushed about 75% of NO3-N (297 g/m2), 80% of DON (1,121 g/m2) and 38% of TDS (1,541 g/m2). With an estimated 2 feet of recharge from the Mid treatment, calculated average leachate concentrations were 600 mg-N/l of NO3-N, 2,255 mg-N/L of DON and 3,100 mg/L of TDS. Under the High treatment in which over 6 feet of water was recharged, 90% of NO3-N (360 g/m2) and DON (1,223 g/m2) was flushed and 62% of TDS (2,511 g/m2) was flushed. However, with the greater amount of leachate, average calculated constituent concentrations for the High treatment were lower than the Mid treatment; 220 mg-N/L for NO3-N, 798 mg-N/L for DON and 1,550 mg/L for TDS. Thus, while the higher recharge rate increased load exports by about 20% for NO3-N, 10% for DON and 60% for TDS, it decreased leachate concentrations by 37% for NO3-N, 35% for DON and 50% for TDS. DON exports were about 4X those of NO3-N and may in part be attributed to use of manure and the manure application timing relative to recharge. In general, recharge at this site has led to significant reductions in NO3-N, DON, and TDS within the studied depth (31'or 945 cm). Based on evidence of both piston flow and non-uniform flow, it is unlikely that all constituents flushed from this depth will reach the groundwater at the same time. Effects on groundwater will depend upon the period, frequency, and leachate concentrations versus groundwater concentrations. Sampling and analyses of groundwater from shallow wells near sites before and after recharge may help in evaluating the effect, if any, of recharge on shallow groundwater quality.

Water Availability and Rates

Water for the Chowchilla orchard is supplied by the Chowchilla Water District (CWD), and their source is water from the USCOE Buchanan Dam plus Class I and Class II water from the Central Valley Project – Friant Division. Availability of the water, rates, and start of release are dependent on rainfall and system storage. For example, CWD did not release any water for irrigation during the drought years of 2014 and 2015. CWD started releases in 2016 on March 18, and January 11 in 2017. Rates are also dependent on supply. The rates for 2016 and 2017 are on Table 6.

Table 6. Cost and availability of water

	Early Spring Release/Rate Dates	Spring Rate (per acre-foot)	Spring/Summer Start Date	Spring/Summer Rate (acre-foot)
2014	No water available			
2015	No water available			
2016	March 18 - April 30	$95	May 1	$118
2017	January 11 - March 26	$5	March 27	$75

During the pilot project conducted in 2016, the cost of recharge water was $118 per acre foot for a total recharge water cost of $10,974. The almond orchard owner reported conducting recharge during January and February 2017, and the cost of recharge water was $5 per acre foot. Assuming a similar volume of water was recharged in 2017 the total recharge water cost would have been $465.

To summarize, the CWD availability and cost of recharge water is variable, and cost-effective recharge would need to be conducted on an opportunistic basis early in the irrigation season of wet years or whenever water rates drop. Systems should be set in place to take advantage of low cost recharge water during wet years.

Conclusions

Under these treatments, VWC at all measured soil profile locations did not reach saturation (with one exception in the High treatment at depth of 3" (7.5 cm)). This finding suggests water moved through the root zone fast enough to avoid extended saturation under intermittent summertime flood irrigation. The farmer's method of applying water to each check twice per recharge event at the High treatment, and allowing 1.5 to 3.5 days between flood events, may have helped to avoid saturation by limiting the volume of water added at any one time. Studies at other locations with different soil properties and/or varied irrigation practices would help in determining when OFFCR may lead to saturated conditions that may threaten crop health. With greater recharge, the period VWC exceeded field capacity (Fc) increased for each soil depth. At 48" (122cm) in the Mid and High treatments, Fc was exceeded on average 5 and 8.5 days respectively, identifying periods in which water flowed past the root zone. Drainage past the root zone did not occur under the Control treatment. Significant variability occurred at monitoring locations within a treatment attributed to differences in initial VWC, potential variability in water volume applications within an irrigation check, and the likely heterogeneous nature of preferential flow paths. The observed variability demonstrates the need to have replicated locations for assessing treatment effects on root or vadose zone conditions.

In soil samples collected to 30 feet (915 cm), water content was lower in the shallow zone (< 5ft or 150 cm) and higher and uniform with depth for all treatments. This result was consistent with trees and cover crops drawing water from the upper soils and not the deeper soils, and recharge water moving under piston flow conditions the full length of the soil core (and likely beyond). Piston flow suggests as water flows down the vadose zone, new water displaces old water and water packets move down the vadose zone like dominos. DON peaks were found in the shallower soils for the Control treatments, but had migrated to deeper depths with recharge, with higher recharge treatments having deeper peaks. Similar findings were found for NO3-N, though the shallower peaks in the Control treatments were not found suggesting plant or microbial processing. However, some results suggest deviation from the piston flow model. Most notably, mass calculations for the Mid treatments show greater losses of mass than expected, suggesting preferential flow and preferential constituent transport.

Soil profiles showed some evidence of nitrogen processing in the shallow root zone but not in the deeper vadose zone. The NO3-N/DON ratio was 0.25 in the root zone but higher below 5' or 150 cm (0.3) and stable throughout the remaining soil core length. The lower NO3-N/DON ratio in the shallower soil indicates plant uptake or other processes have reduced the concentration of NO3-N relative to DON in the root zone, but below 5' (150 cm) those processes seem to shut down.

Nitrogen and salt mass losses were calculated for the different treatments. The Mid treatment, with 20 inches (50 cm) recharge, flushed about 75% of NO3-N, 80% DON and 38% TDS. Under the High treatment in which over 64 inches (162 cm) of water was recharged, 90% of NO3-N and DON was flushed and 62% of TDS was flushed. Thus, the higher recharge rates increased load exports by about 20% for NO3-N, 10% for DON and 60% for TDS. However, due to the greater amount of flushing, average calculated concentrations of constituents in the leachate were lower by 37%(NO3-N), 35% (DON) and 50% (TDS) for the High treatment as compared to the Mid treatment.

Evidence from this study suggests constituents will not be flushed to groundwater at the same rate and arrive at the same time. Groundwater well sampling would be helpful in better understanding potential effects on groundwater and their management. In general, this project resulted in significant recharge during the summer season up to a total of 6 feet and showed with higher recharge rates, water quality loading and concentrations have relative decreases. Recharge did not appear to affect yields though long-term agronomic affects are uncertain.

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Supplemental Information

Figures

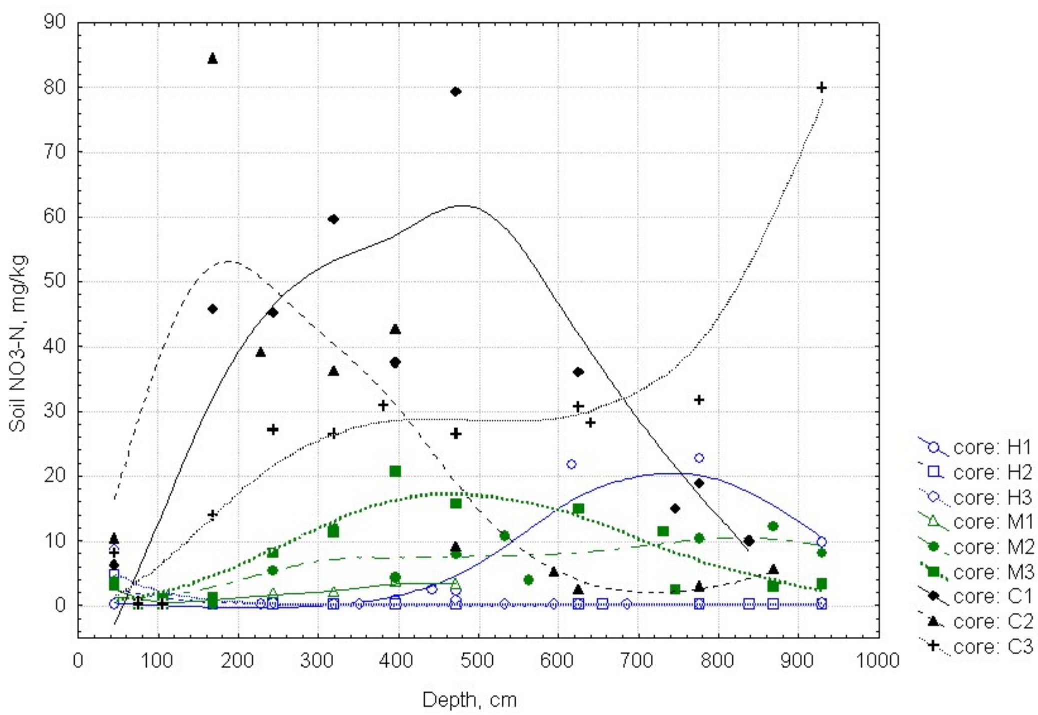

Figure 12. NO3-N (NO3-N) Concentrations in Soil (mg/kg)

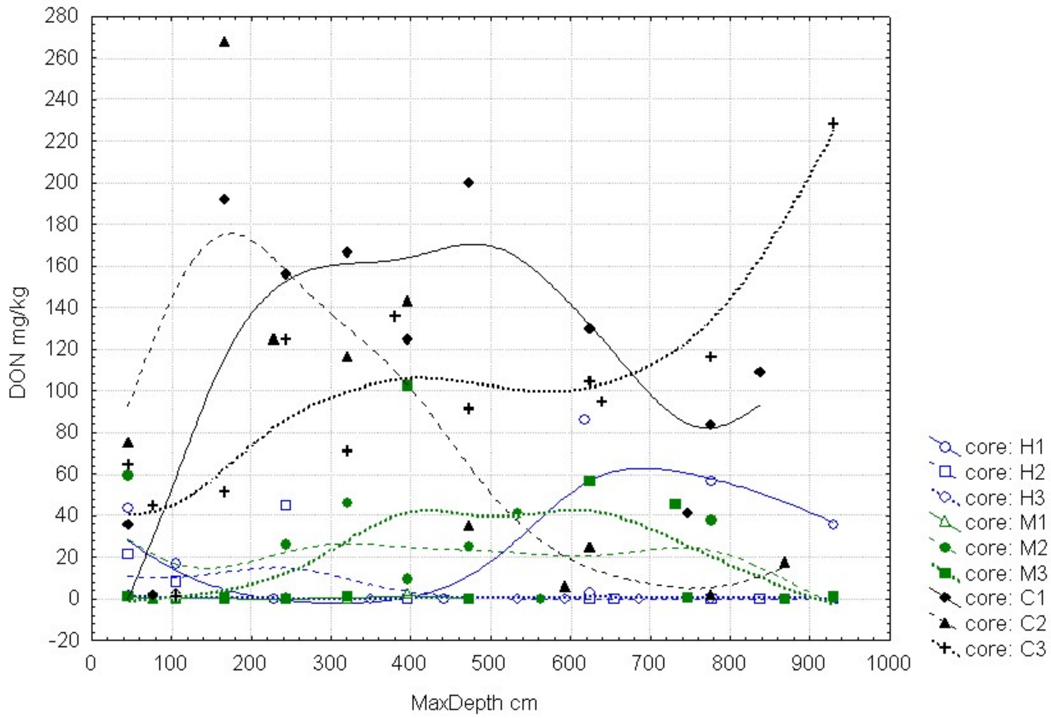

Figure 13. Dissolved Organic Nitrogen (DON-N) Concentrations in Soil (mg/kg)

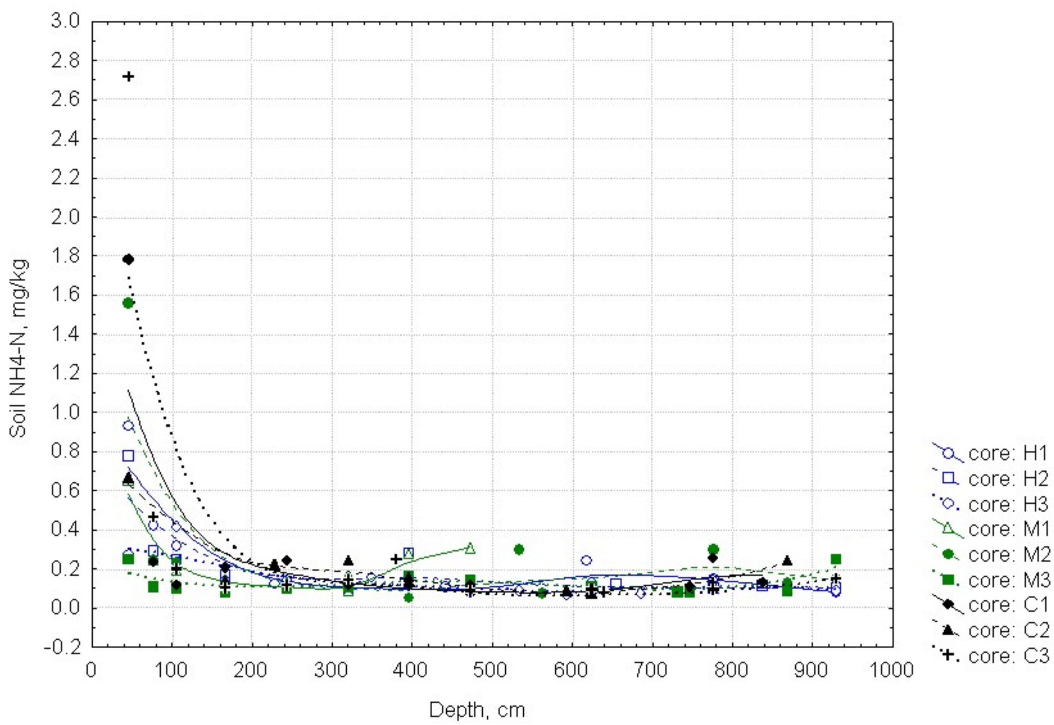

Figure 14. Ammonium (NH4-N) Concentrations in Soil (mg/kg)

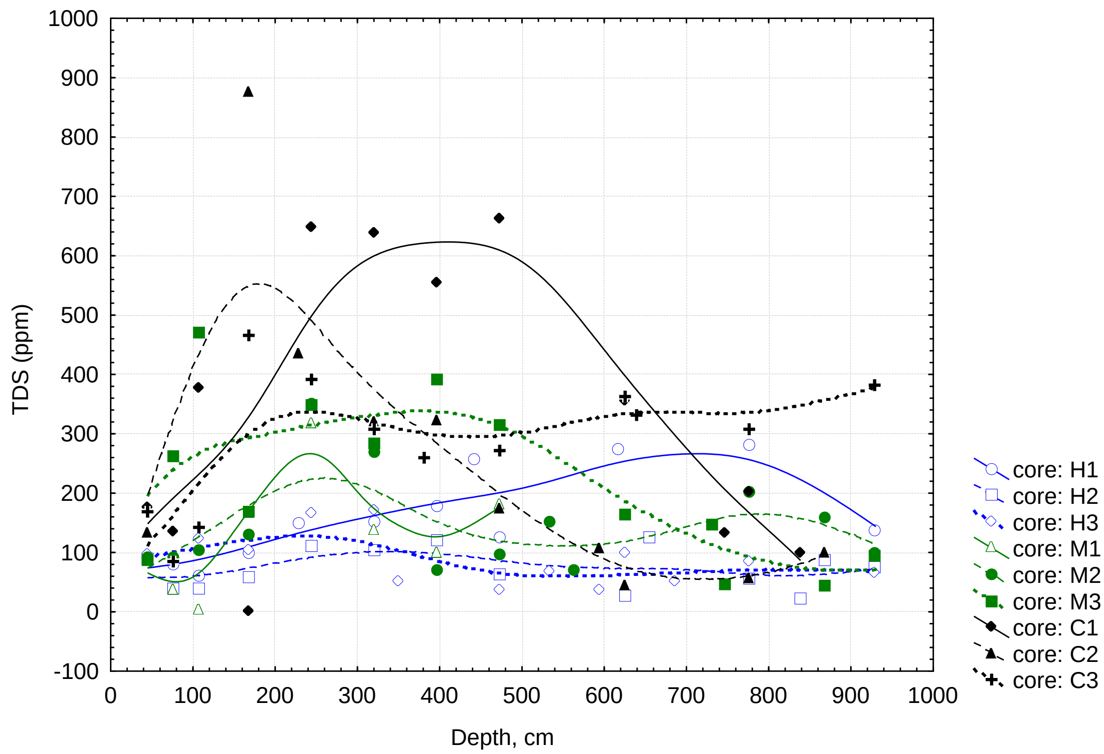

Figure 15. TDS concentrations in Soil (ppm, mg/kg)