Winter Water Management in Almonds

Project No.: **17-PREC9A-Volder**

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Objectives:

Follow the impact of winter water application for recharge purposes at three field sites in Modesto, Delhi, and Orland. At these sites we aim to conduct field studies to test the effectiveness of winter/late spring irrigation as a sustainable groundwater recharge strategy and document any negative or positive effects of winter irrigation on almond yield, water status or root development. A second objective is to determine the threshold level of dormant tree water stress (SWP) indicating the need for pre-bloom irrigation in dry winters.

Interpretive Summary:

We are monitoring the impact of winter water application with the express intent to recharge groundwater at three locations, near Modesto, Delhi, and Orland. In addition, we are conducting a controlled pot experiment to test whether winter irrigation may have positive effects on tree health and flowering during periods of winter drought. Dormant drought stress caused a substantial (10 – 20 day) delay in flower bud development and the date of first bloom but did not have a significant effect on leaf out date. However even though bloom was delayed, fruits formed on all trees, and kernels developed normally.

Materials and Methods:

A number of factors have led to a reduction in groundwater recharge in California, and in some parts of the state groundwater levels have exceeded historic lows. In order to sustain water security and agricultural production in California a new technology is explored where farmland (e.g. almond orchards) is flooded during the winter using surface water to recharge the underlying groundwater. Applying excess surface water, when and where available, to almond orchards during dormancy, could potentially save surface water for use to respond to critical environmental needs such as enhanced environmental streamflow. A key assumption of this approach, however, is that almond trees will need to tolerate saturated or near saturated soil conditions during dormancy and/or late spring. An equally important question is whether winter irrigation is necessary during dry years and whether dormant almond trees are negatively impacted by drought during dormancy.

Water balance and soil nutrient analyses

During the 2015/2016 winter, groundwater recharge experiments were conducted on two almond orchards located near Modesto, CA and Delhi, CA, respectively. In 2016/17 a third site was added near Orland, CA. In each orchard three treatment plots were established: 1) no winter irrigation (in case the grower winter irrigated), 2) winter recharge irrigation with 24 inches of water in addition to rainfall (flood), and 3) grower control. The flood and grower control plots were each instrumented with Decagon 5-TM and 5-TE soil moisture sensors at 0.5 ft and 1.5 ft depth. The deeper sensors also allowed measurement of the soil electrical conductivity. In winter of 2016/17 additional soil moisture sensors (Decagon GS-1) were installed at each site at 3.2 ft (1m) depth. On each plot the control volume applied to the test plots, the infiltration rate of the applied water into the soil and passed the root zone, and the soil water content within the root zone were determined. Applied water was measured either with flow meters (e.g. at the Orland site using a Greyline acoustic flow meter) or by the ditch tender (Modesto, Delhi). At each site soil cores were taken to a maximum depth of 16 ft before (Oct-December) and after recharge events using a Geoprobe push drill. At each site three cores were taken in each treatment per coring event. Soil cores were analyzed for soil moisture content, texture, pH, EC, and soil nitrate. Soil texture was determined from soil cores using the pipette method and bulk density from undisturbed soil samples, respectively (USDA-NRCS 2004). Samples were extracted with 2 M KCl solution and NO3-concentrations were determined colorimetrically (Doane and Horwath, 2003).

A water balance model based on the Thornthwaite-Mather (TM) procedure (Steenhuis and Van der Molen 1986; Dahlke et al. 2017) was set up for each site to estimate the fraction of the applied winter water going to deep percolation or groundwater recharge. Recharge, ***R***, was estimated using the following water balance equation:

$$\boldsymbol{R_t = I_t + P_t - ET_t - \Delta S_t - Q_t} \qquad (1)$$

Where $\boldsymbol{I_t}$ is the amount of applied winter water (in) at time t, $\boldsymbol{P}$ is precipitation (in), **ET** is evapotranspiration (in), **ΔS** the change in soil storage (in) (dependent on the available water capacity (AWC) of the soil), and $\boldsymbol{Q}$ is surface runoff (in). Q was considered to be negligible since all applied water infiltrated in the recharge plots. For each treatment, I was estimated from water application rates divided by the application area. The TM model was run for the rainy season (Oct. 1 to Mar. 31 of following year) at an hourly time step. Potential evapotranspiration (CIMIS ET_o) was obtained as hourly data from the CIMIS station in Durham (#12) for the Orland site, from the Modesto (#71) for the Modesto site, and from Denair II station (#206) for the Delhi site (CIMIS 2011). In the TM water balance model, the change in available soil water (ΔS) is dependent on the total available water capacity (AWC) (cm) of the soil. For all sites AWC was estimated for a 45cm deep soil profile from field-measured soil water content data by fitting the following 1D saturated–unsaturated flow equation (Steenhuis et al. 1984):

$$\theta_t = \theta_d - \frac{\theta_s - \theta_d}{\kappa} ln\left[\frac{\kappa K_{sat} \Delta t \exp(-\kappa)}{L(\theta_s - \theta_d)} + \exp\left(-\kappa \frac{\theta_{t-\Delta t} - \theta_d}{\theta_s - \theta_d}\right)\right] \qquad (2)$$

Where θ_t is the volumetric water content (volume fraction) at time t, θ_s and θ_d are the volumetric water contents at field capacity and wilting point (volume fraction), κ is a constant (positive), K_{sat} is the saturated hydraulic conductivity, and Δt is the time step (Steenhuis et al. 1984).

For each site κ, θ_s and θ_d were calibrated using the Newton-Raphson solver, from which the final AWC was estimated as the difference between the water content at field capacity (θ_s) and wilting point (θ_d). At each site, duplicate volumetric water content sensors (Decagon 5-TM and 5-TE) and 2 ft tensiometers (Irrometer model RSU-S, Irrometer Inc.) were installed in the recharge and control plots at 0.5ft and 1.5 ft depth in hand-augured holes. Soil hydraulic properties and estimated van Genuchten parameters are summarized in **Table 2** for all sites.

The TM model was initiated by assuming that the soil water content was at 50% of field capacity at the beginning of the simulation period (10/1/2014). Besides rainfall and applied winter water amounts no additional water, such as growing season irrigation, was considered in the water balance. The TM model was only applied to the upper root zone (upper 1.5ft) for which soil water content data was available.

Tree health and root production

The experimental design was such that both at Modesto and Delhi each treatment was only replicated once, while at Orland each treatment was replicated three times. Five trees were intensively monitored for stem water potential and root production within each replicate treatment. Stem water potential was collected regularly with a pressure chamber and root growth was monitored using a minirhizotron technique where 90 cm long clear observation tubes are installed in the root zone at a 45o angle (down to 50 cm). Outward scans (CID bioscience root scanner) of the root zone are collected every three weeks at four depths by inserting a root scanner in the tube and scanning the tube soil interface. Images are then processed for the appearance and disappearance of roots during the three-week interval using RootFly software (Clemson University) by manually indicating new roots and marking the disappearance of older roots. Tree canopy light interception was measured using the light bar (Lampinen et al.) or using the iPAR app on an iPhone. Each treatment was harvested at the end of the growing season and yield was determined.

Pre-bloom irrigation in dry winters

Two field sites (Modesto and Delhi) include one block available for testing the importance of irrigation during a dry winter, but thus far winter rain has been adequate. In order to experimentally test for the combined effects of timing and degree of water stress during dormancy on tree physiology and bloom development, nonpareil trees grown in large (12 gal) pots in an outdoor nursery were irrigated normally during the growing season but exposed to different levels of drought for different periods of time during dormancy. In early December, all trees were moved to a covered outdoor area to protect from rain, and the soil dried using a cover crop to achieve moderate (-10 bars) and severe (-20 bars) target levels of tree water stress (measured by SWP). These levels of stress were held for about 20, 40, or 60 days, simulating short, medium, or long drought conditions during dormancy, before being irrigated prior to flowering. Each treatment was represented by five trees and all treatments were compared to control trees which were kept well irrigated (-2 to -4 bars) throughout dormancy. All trees were moved back to the initial location once the longest drought period had been completed and irrigated to maintain adequate soil moisture through bloom and fruit set. During dormancy, SWP was monitored to verify/adjust target treatment levels in each individual tree, buds were examined for any drought effects on flower development, and twig samples were collected for carbohydrate analysis. During the bloom period, flower development was monitored three times weekly on two individual tagged branches per tree, recording the number of buds open at each date. Pollinator bloom was maintained throughout the bloom period by importing pollinator flowering branches, and fruit set was confirmed by visual examination. Any differences in flower development were related to the measured timing and degree of dormant water stress experienced by each individual tree.

Results and Discussion:

Water Balance and Deep Percolation Analysis.
The winter of 2016/2017 was an exceptional wet winter in northern California and an above average winter in central California. Total rainy season (Oct-April) precipitation amounts were 17.44, 12.46 and 28.86 inches near Delhi, Modesto and Orland, CA, respectively, with most precipitation falling in the months January until April. At the Delhi and Modesto site, a total of 24 inches of water was applied in 3-4 irrigation events on each orchard (**Table 1**). At the Orland sites, 7 recharge events were conducted but only 4.8 inches of water could be effectively applied during these events, before tailwater and surface runoff was generated. The generally wet conditions at the Orland site (Jacinto fine sandy loam, SAGBI rating moderately poor) kept the soil water content overall near field capacity, which combined with low soil hydraulic conductivity and soil infiltration capacity resulted in slow drainage (**Figure 1 & 2**). This is further corroborated by the small amplitude in the observed volumetric water content. The small amplitude indicates low soil water storage in the soil profile, which could be caused by a confining layer in the soil profile (e.g. cemented clay horizon), as indicated by the higher water content observed at 1.5 ft depth. Because of the limited soil storage, the soil profile quickly filled up in December as the result of several rain events and stayed at a minimum water content of 0.3 throughout January-March. Subsequent rain and recharge events caused a spike in the volumetric water content to field capacity followed by a slow and long recession.

Table 1: Irrigation events and total applied water amounts for the winter recharge experiments conducted in Delhi and Modesto, CA.

Modesto		Delhi		Orland	
Date	Inches Applied	Date	Inches Applied	Date	Inches Applied
1/4/2016	6	12/23/2015	6		
1/11/2016	6	12/29/2015	9		
1/19/2016	6	01/12/2016	10		
1/25/2016	6				
1/9/2017	6	1/13/2017	14.4	12/22/2016	1.42
1/16/2017	6	1/19/2017	5.7	12/27/2016	1.04
1/23/2017	6	1/26/2017	5.7	1/13/2017	0.48
2/1/2017	6			1/16/2017	0.54
				1/25/2017	0.45
				1/28/2017	0.44
				1/31/2017	0.40

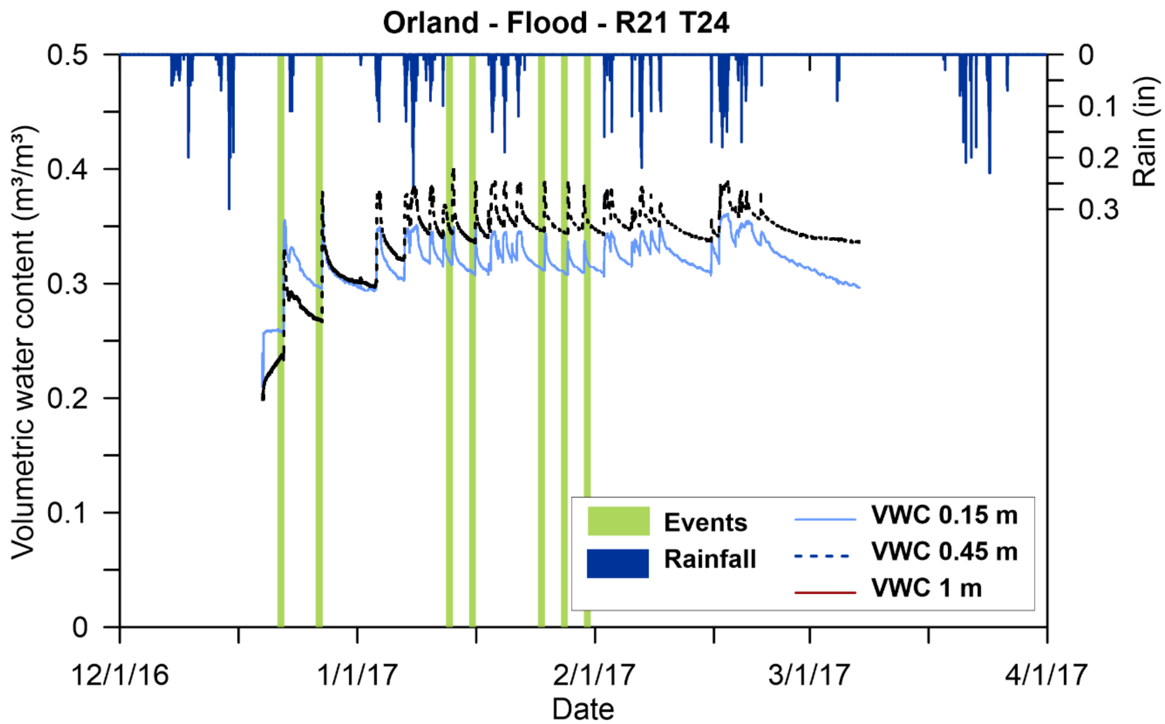

Figure 1: Volumetric soil water content measured at 0.5 ft (15cm) and 1.5 ft (45 cm) depth in the flood treatment in Orland, CA. Green bars indicate the recharge events.

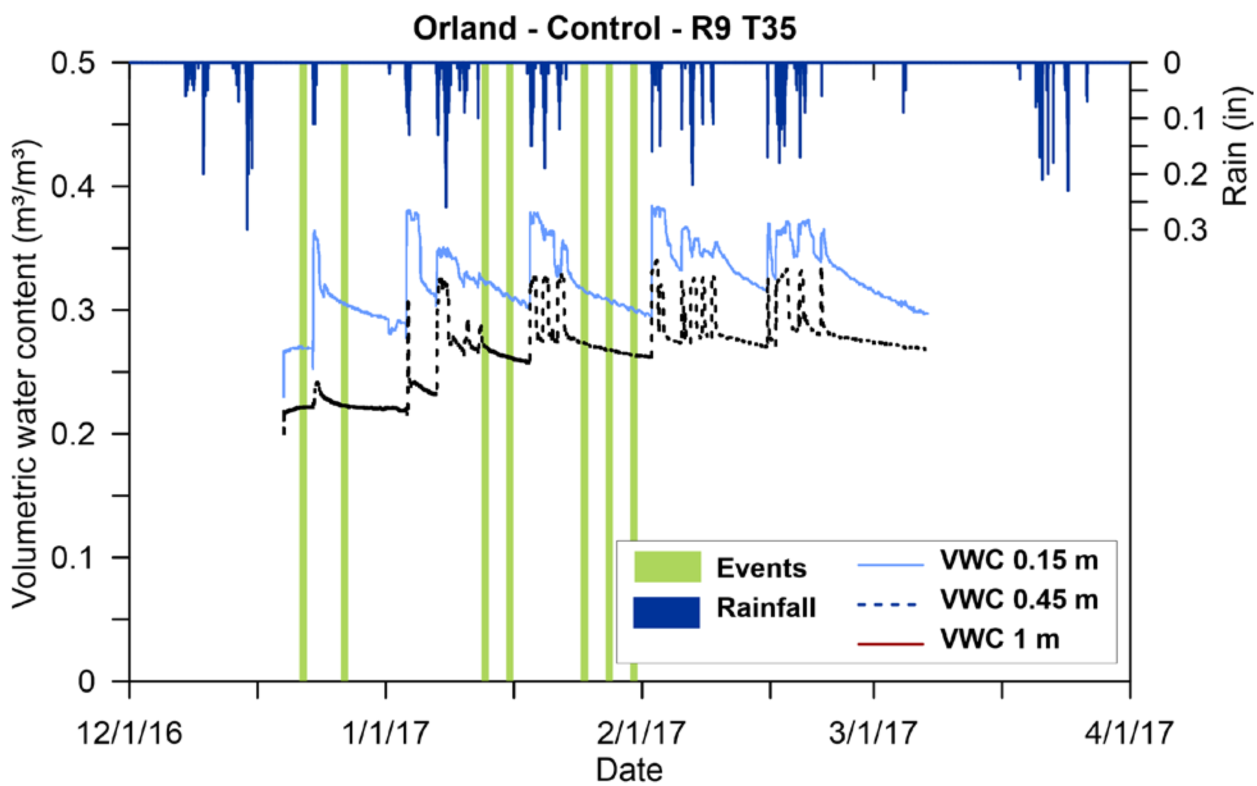

Figure 2: Volumetric soil water content measured at 0.5 ft (15cm) and 1.5 ft (45 cm) depth in the flood treatment in Orland, CA. Green bars indicate the recharge events.

At the Modesto site (Dinuba fine sandy loam, SAGBI rating Moderately Good) the soil water content increased to field capacity and saturated conditions during each water application event (**Figure 3**). During each event, 6 inches of water were applied via flood irrigation over a period of 4-6 hours. As was observed in the winter of 2015/16, saturated conditions prevailed for up to 48 hours after each water application, after which the soil moisture content dropped back to pre-event values. For the later water applications, it took up to 72 hours for the soil water content to drop back to pre-storm values. As shown in **Figure 3** and **4** some of the higher intensity rainfall events that occurred in December and mid-February to mid-March caused short-lived spikes in the soil water content to field capacity. After mid-April the soil moisture data show a steady depletion in soil water content throughout the beginning of the growing season. Interestingly, at the beginning of the 2017 growing season the deeper soil moisture sensors (at 1m) in the flood treatment showed a quicker depletion in soil water content than the shallow sensors, indicating that the trees take up water from the deeper soil profile and that the irrigation events are not sufficient to replenish the deeper soil profile (**Figures 3 & 4**). This pattern could not be observed in the control treatment, suggesting that local soil differences in the orchard impact irrigation management.

Despite the wetter winter, the oxidation-reduction potential sensors installed at 20 cm depth indicate that throughout the wet February at no time did the high soil water content create reduced conditions in the root zone. This is a positive observation that encourages further study in concert with the root growth analysis.

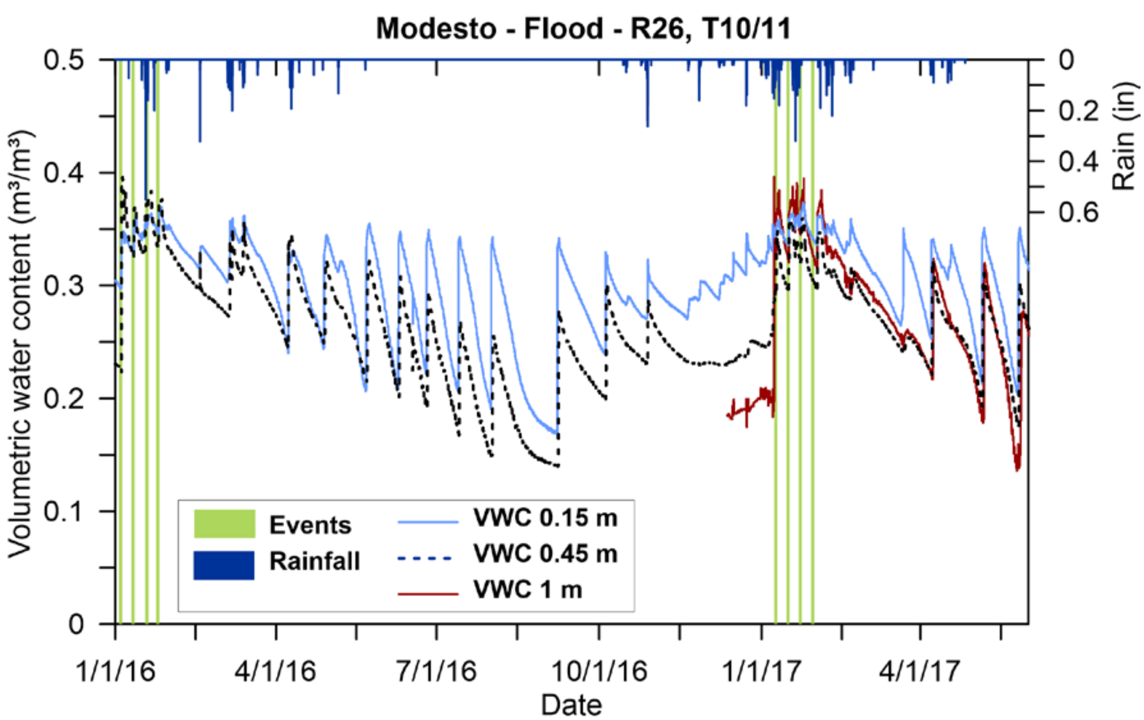

Figure 3: Volumetric soil water content measured at 0.5 ft (15cm), 1.5 ft (45 cm) and 3.3ft (1m) depth in the flood treatment in Modesto, CA. Green bars indicate the recharge events.

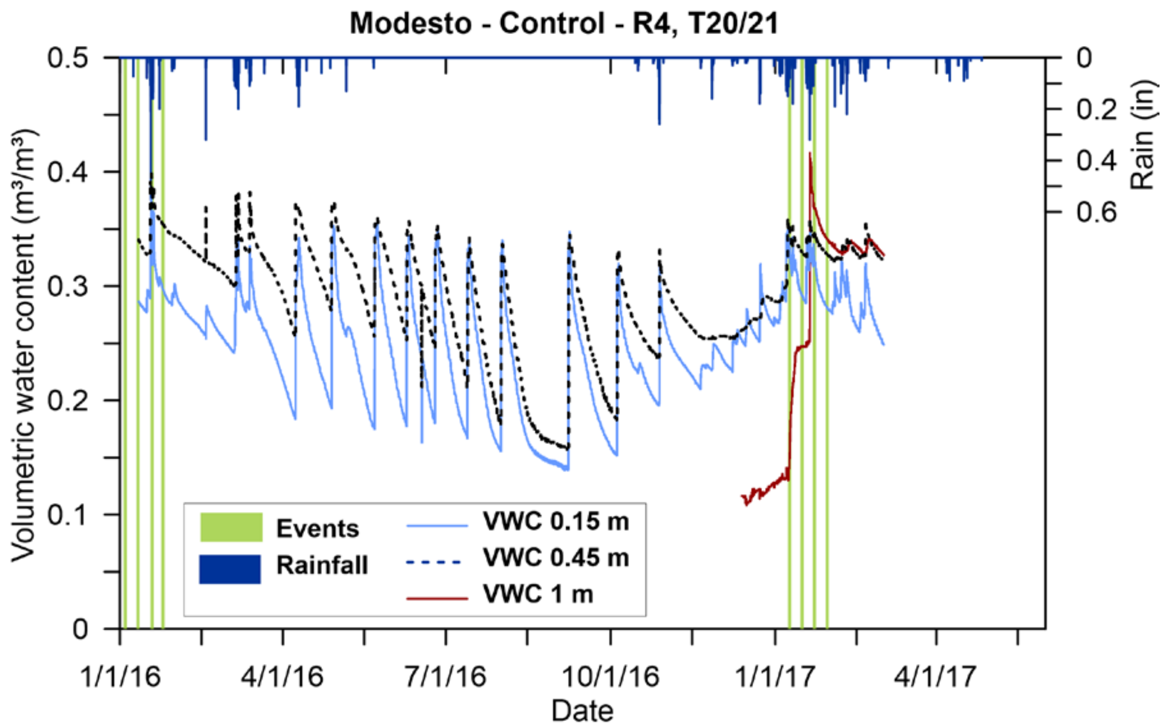

Figure 4: Volumetric soil water content measured at 0.5 ft (15cm), 1.5 ft (45 cm) and 3.3ft (1m) depth in the flood treatment in Modesto, CA. Green bars indicate the recharge events.

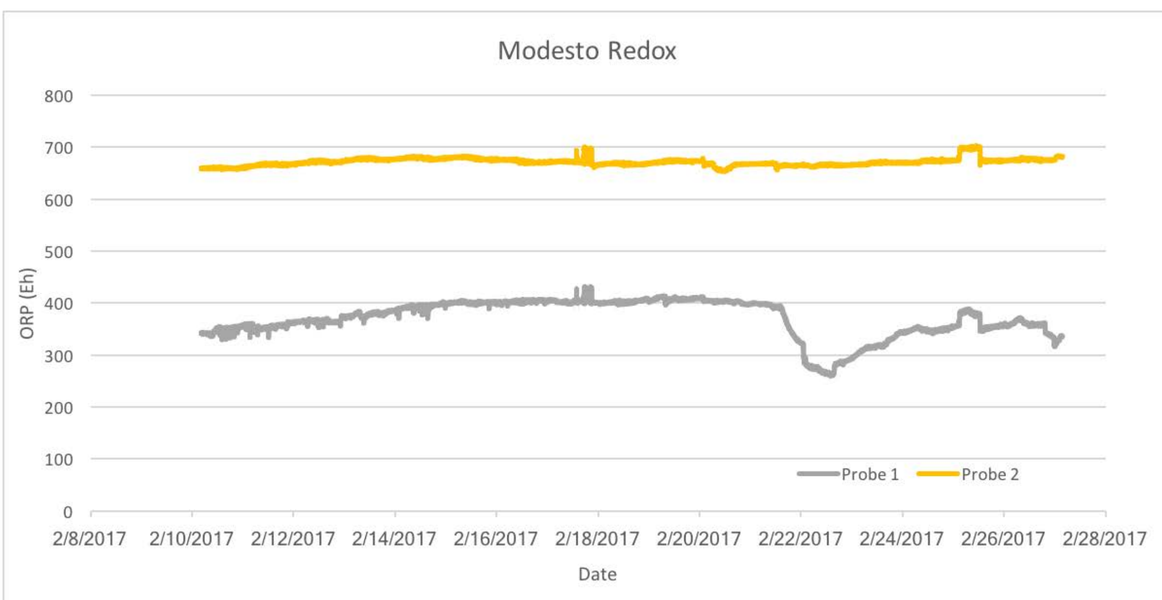

Figure 5: Oxidation-Reduction Potential measured at 20 cm (8 inches) depth in the flood treatment at Modesto, CA.

In contrast to the Modesto and Orland sites, the sandier Delhi site (Dune land, sand, SAGBI rating Excellent) showed much quicker infiltration of the applied winter water. As shown in **Figure 4** and **Table 1** a total of 25.9 inches of water were applied in three events of 14.5, 5.7 and 5.7 inches, respectively. In contrast to 2015/16 the soil water content was overall higher in the orchard at the beginning of the rainy season as the result of several large rainfall events in November-December. Both the shallow and deep soil moisture sensor showed an immediate response to the first water application on January 13, 2017 and peaked to a soil water content of about 0.4 m^3/m^3 during each event, indicating that the soil pore space was filled quickly with the percolating water. In the flood treatment both shallow and deep soil moisture sensors dropped to pre-application water contents within 12 hours after the water was applied. Overall the sensor data indicates that the volumetric water content stayed around 10-15% in the shallow root zone throughout the growing season of 2016. Similar to the Modesto site, neither the winter water application nor the rainfall events caused water logged or reduced conditions in the root zone at the Delhi site (**Figure 8**).

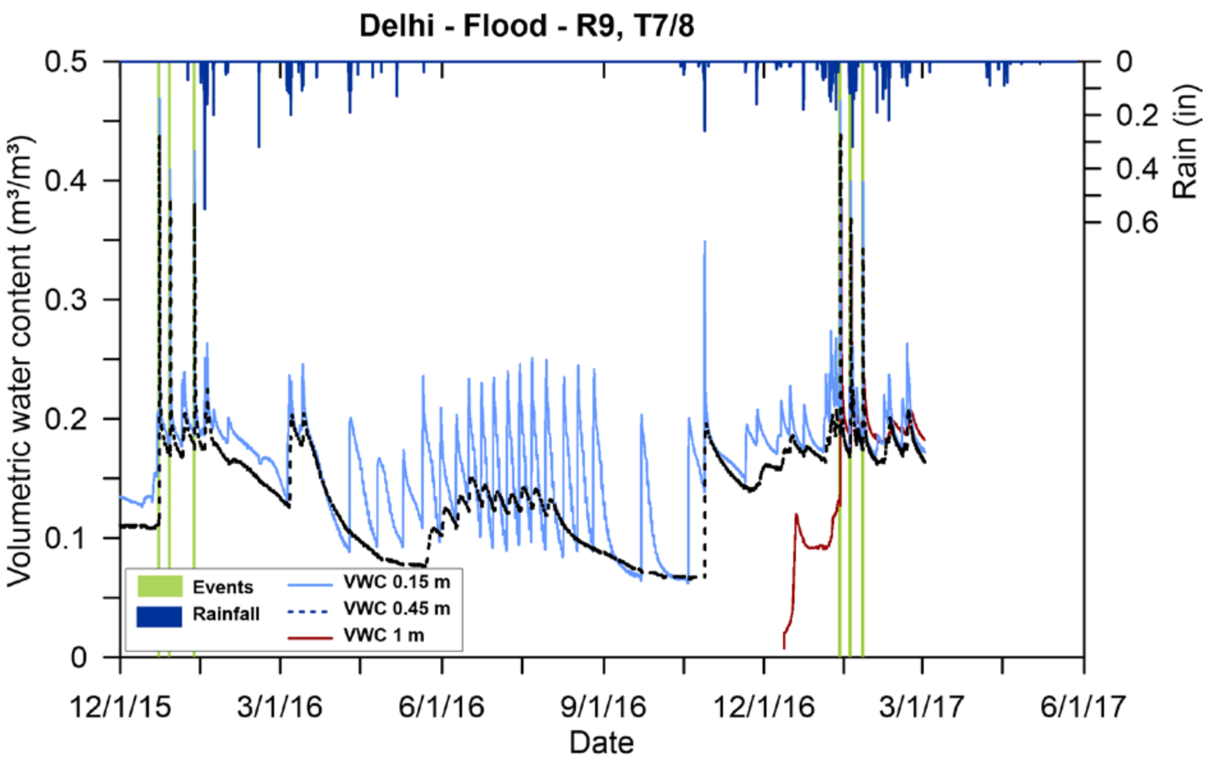

Figure 6: Volumetric soil water content measured at 0.5 ft (15cm), 1.5 ft (45 cm) and 3.3ft (1m) depth in the flood treatment in Delhi, CA. Green bars indicate the recharge events.

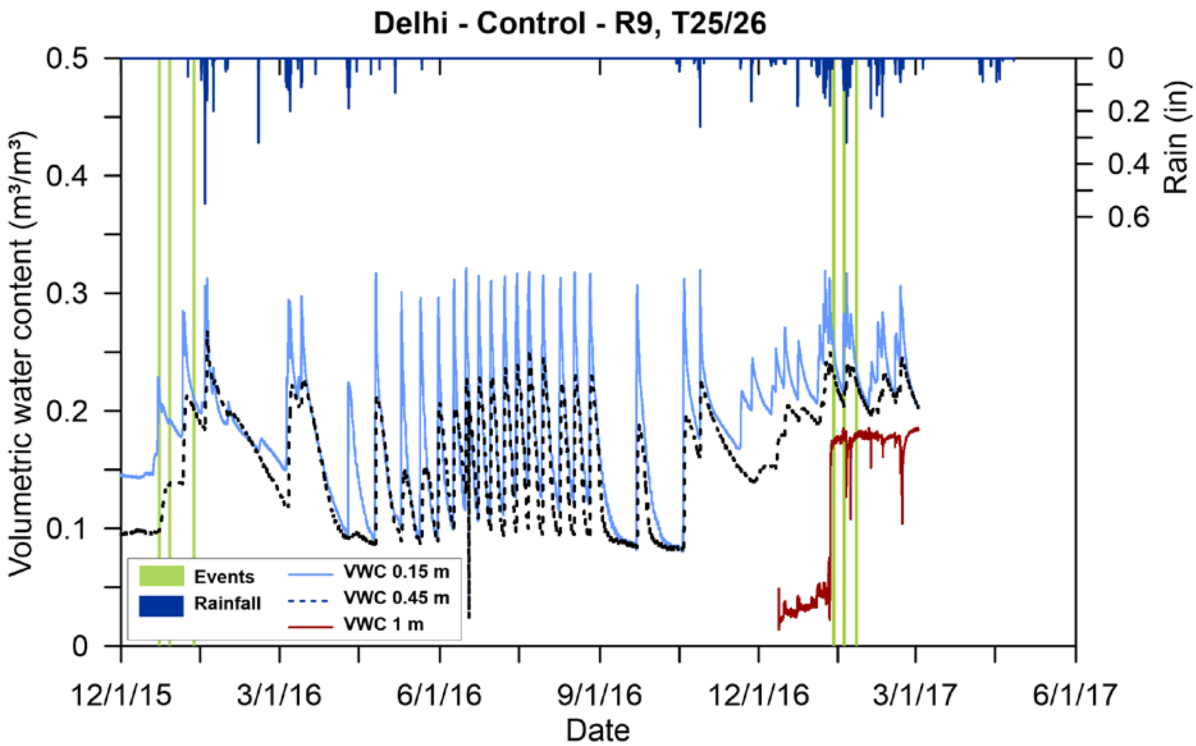

Figure 7: Volumetric soil water content measured at 0.5 ft (15cm), 1.5 ft (45 cm) and 3.3ft (1m) depth in the flood treatment in Delhi, CA. Green bars indicate the recharge events.

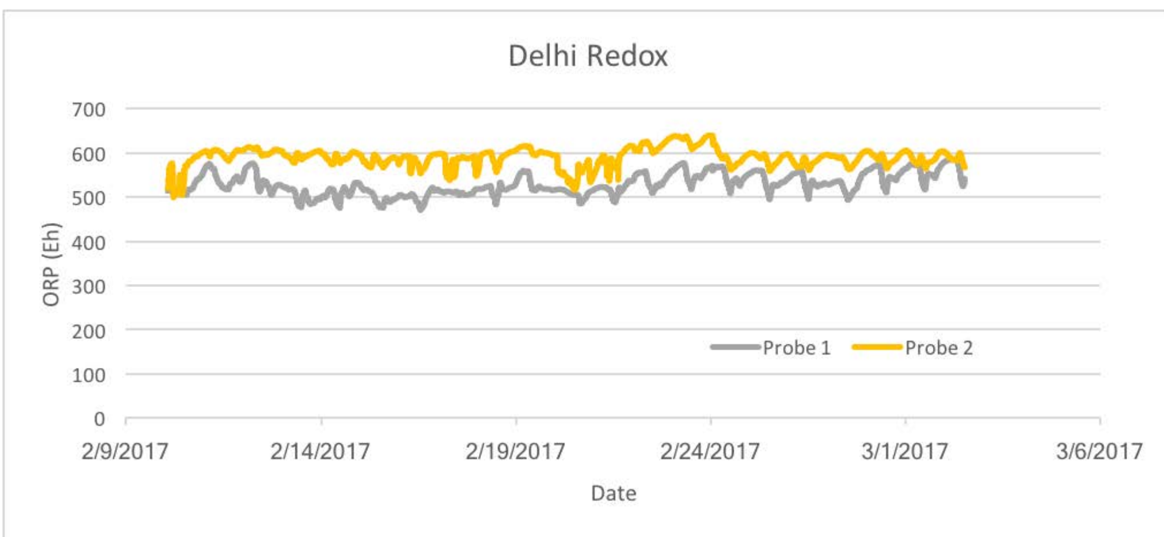

Figure 8: Oxidation-Reduction potential measured at 20 cm (8 inches) depth in the flood treatment at Delhi, CA.

Table 2: Water retention and hydraulic conductivity parameters fitted with a 1D vertical flow model. AWC is given for a 1m soil column.

	Delhi	Modesto	Orland
AWC (in [cm])	11.0 [28]	13.8 [35]	5.1 [13]
θ_d (in^3/in^3)	0.0	0.03	0.20
θ_s (in^3/in^3)	0.28	0.38	0.33
κ (-)	19.78	31.35	19.49
α (1/in)	0.261	0.017	0.01
n (-)	1.5	2.055	2.055
K_{sat} (in/day)	473	189	45.6
NSE[a]	0.85	0.86	0.85

[a] Nash- Sutcliff coefficient (Nash & Sutcliff 1970)

For each site, the 1D saturated/unsaturated flow model was used to estimate the total soil water storage capacity (AWC), the wilting point and field capacity (θd and θs), and the average hydraulic conductivity of the soil profile. Estimated parameters are summarized in **Table 2**. Depending on the texture of the soil, the three sites showed very different available water capacities, with Orland providing the lowest (5.1 inches) and Modesto the highest (13.8 inches). Similarly, saturated hydraulic conductivities ranged between 45.6 inches/day at the Orland site to 473 inches/ day (39 ft/day), reflecting the drainage properties observed in the field.

For each site, a variable amount of each water application was used to fill the empty pore space in the soil profile, and as the water application progressed, water filled pore space increased from field capacity (water retained in soil by gravity) to saturation (freely drainable water) (O'Geen 2012). Total deep percolation amounts (i.e. including recharge from rainfall) were similar at the Delhi site for both winter recharge years. Deep percolation amounts were 24.3 and 25.6 inches, respectively in 2015/16 and 2016/17 (**Table 3**). About 93-99% of the applied winter water passed through the root zone (45 cm) as deep percolation. Depending on the timing of the winter water application with respect to antecedent rainfall, about 0.2 to 1.8 inches of the applied winter water was used to satisfy evapotranspiration and to bring the water content in the root zone to saturation.

For the Modesto sites, deep percolation amounts were more variable between both years (**Table 3**). In the drier 2015/16 winter only 81% of the applied water (19.35 inches) went to deep percolation, while 4.65 were retained to bring the soil to field capacity and to satisfy evapotranspiration. In the wetter 2016/17 winter 96% of the applied winter water went to deep percolation and only 0.84 inches were needed to fill up air filled pore space in the fine sandy loam.

At the Orland site, poor drainage of the soil profile prevented percolation of large amounts of the applied winter water. For most winter water applications, the soil profile was already filled from rainwater while a confined layer slowed percolation to the deeper soil profile. Thus only 4.76 inches of winter water could be applied to the flood treatments of which 3.65 inches (77%) percolated deeper into the profile. An estimated 21 inches of the 28.6 inches of winter precipitation percolated through the profile. The remainder (1.11 inches of the applied water) went to evapotranspiration or was used to bring soils to field capacity and saturation.

Table 3: Summary of water inputs (precipitation and applied winter water) and estimated deep percolation and losses for the three experimental sites.

	Precipitation	Applied Water	Total deep percolation	Deep Percolation from rainfall	Deep Percolation of applied water		Loss of applied water to soil storage	
	inches	inches	inches	Inches	inches	%	inches	%
Delhi (Oct - Mar) 2015/2016	12.94	26.15	29.09	4.79	24.30	93%	1.84	7%
Delhi (Oct - Mar) 2016/2017	17.44	25.80	33.03	7.43	25.60	99%	0.20	1%
Modesto (Nov - Mar) 2015/2016	9.91	24.00	21.90	2.55	19.35	81%	4.65	19%
Modesto (Oct - Mar) 2016/2017	12.46	24.00	27.94	4.78	23.16	96%	0.84	4%
Orland (Dec - Mar) 2016/2017	28.62	4.76	21.00	17.35	3.65	77%	1.11	23%

Soil Nitrate

Three soil cores were drilled in each treatment plot at the Delhi and Modesto sites prior to (October 2015) and after (February 2016) the winter recharge experiments in 2015/16. The same number of soil cores were drilled in November 2016 (before recharge events) and March 2017 (after recharge events), however, soil analysis of these cores has not been finished. The 1.5-inch diameter soil cores were extracted with a department-owned Geoprobe push drill. Soil cores were drilled to a depth of 14-16 ft. **Figures 9** and **10** show the plot layout for the Modesto and Delhi site. **Figures 11** and **12** show the soil stratigraphy, biogeochemical and textural data extracted from the flood treatment plot and the control at the Modesto and Delhi sites. The soil stratigraphy at the Modesto site clearly indicates a clay-rich layers at 130 cm depth in the flood treatment and at 100 cm depth in the control (**Figure 11**). Soil nitrate-N in the root zone and deeper vadose zone was relatively low (3-10 ppm) in both treatments prior to the recharge events and mainly concentrated in the deeper soil profile at 220-320 cm depth. In contrast, electrical conductivity (EC) was higher in the upper part of the soil profile but overall low (40-640 µS/cm). Comparison of the soil nitrate-N and soil EC before and after the recharge events indicates mobilization of solutes into the deeper vadose zone and accumulation above a cemented clay layer at 360 cm depth. There was also a stark increase in soil nitrate in the top soil (first 20 cm), which might be the result of N mineralization and nitrification due to the higher soil carbon and microbial content in the upper root zone.

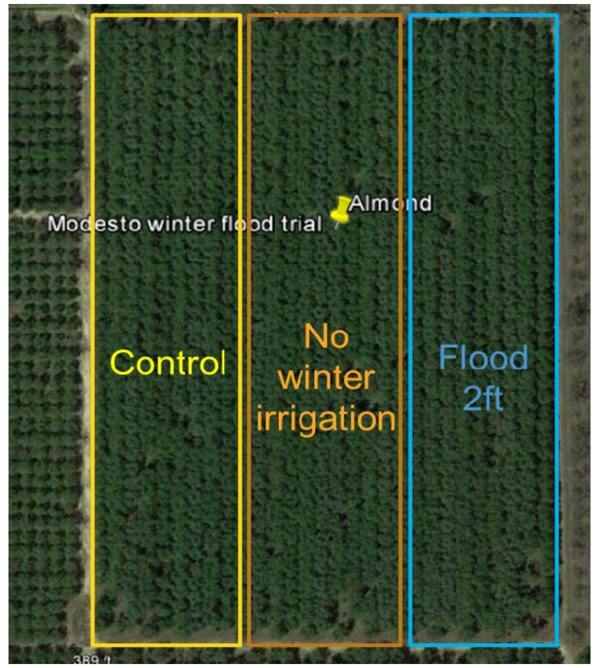

Figure 9: Plot layout at the Modesto site. Irrigation direction is from North to South.

The soil stratigraphy at the Delhi site consists of varieties of sand in the flood treatment and increasingly finer materials (silt loam and silt) in the control (**Figure 12**). It is noteworthy to mention that the Delhi site has the smallest plot size among all sites, consisting of 5 rows by 10 trees (**Figure 10**). Soil nitrate-N in the root zone and deeper vadose zone was relatively low (3-10 ppm) in the flood treatments prior to the recharge events and mainly concentrated in the deeper soil profile at 200-300 cm depth. In contrast, soil nitrate in the two control plots (grower standard and no winter irrigation) were one order of magnitude higher than in the flood treatment, reaching 100 ppm NO3-N at a depth of 120-300 cm (depth below the root zone). Both treatments also showed a stark contrast in electrical conductivity following the same trend as was observed for the soil nitrate. The flood treatment showed the highest EC (200-300 µS/cm) in the deeper soil profile (>300 cm) while the control showed the highest EC (500-1000 µS/cm) values just below the root zone at 100-300 cm depth.

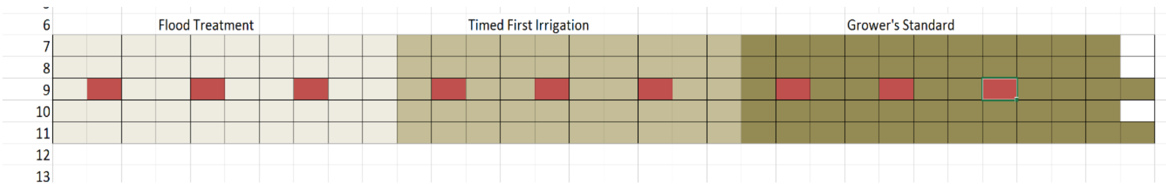

Figure 10: Plot layout for the Delhi site. Irrigation direction is from West to East.

Both sites showed large variability in total profile NO3-N within the orchard as well as across sites during the 2015/16 season. Both orchards also did not show a consistent decrease in soil nitrate after the winter water was applied. To confirm this finding, several soil samples were re-analyzed in the lab to ensure the final soil nitrate values. Total profile NO3-N (sum over all soil horizons within one soil core) at the Modesto site varied between 20 and 220 kg/ha during the 2015/16. Total profile NO3-N was generally lower in the control in both the before and after cores and higher in the flood treatment (with a few exceptions near the center of the orchard). However, most after cores (which were taken within one foot of the before sampling location), showed a slight increase in total profile NO3-N. This increase could be related to the fact that the winter of 2015/16 provided nearly average precipitation after a 4-year drought, thus stimulating biogeochemical processes such as mineralization of organic nitrogen. The nitrate concentration of the applied winter water (storm water from the City of Modesto) ranged between 1.29 and 1.62 ppm.

During the 2016/17 season total profile NO3-N (sum over all soil horizons within one soil core) at the Modesto site varied between 110 and 489 kg/ha in the before cores and 40 and 868 kg/ha in the after cores (**Figure 18**). Overall profile nitrate load was very low in the flood treatment indicating that most soluble nitrate was flushed out of the root zone and upper vadose zone. However, similarly to the 2015/16 season there was an increase in the nitrate load in the top soil layer (0-20cm), which most likely can be attributed to mineralization of organic nitrogen and subsequent denitrification (**Figure 15**).

Total profile NO3-N was four times higher at the Delhi site than the Modesto site during the 2015/16 season, ranging between 50 and 1600 kg/ha for the before and after cores collected in 2015/16. The site showed a clear, increasing trend in total profile NO3-N across the test plots (West to East), suggesting that some of the higher soil nitrate loading is created by irrigation non-uniformity in the sprinkler irrigated orchard. Two of the three locations cored within the flood treatment showed a clear decrease in total nitrate (more than 50%), while most locations in the control plots showed either a slight increase or no clear change in total soil nitrate. The decrease observed in the flood treatment corroborates the hypothesis that large winter water applications in this sandy soil have the potential to remove large amounts of nitrate. However, one also has to remember that the soil in the control contained more fine material than the flood treatment, which allows more retention of soil carbon and possibly soil nitrate in the profile. In addition, the recharge experiment was conducted by pumping groundwater from a nearby well which showed NO3-N concentrations of 8.6 and 10.7 ppm in January 2017, thus adding more nitrate to the profile.

During the 2016/17 season total profile NO3-N (sum over all soil horizons within one soil core) at the Delhi site varied between 60 and 1718 kg/ha in the before cores and 55 and 1736 kg/ha in the after cores (**Figure 17**). Overall the same West-East trend as found during the 2015/16 season was observed with lowest profile NO3-N concentrations on the west end (flood treatment) and highest NO3-N concentrations near the east end of the orchard (control) (**Figure 16**). Most NO3-N in the control plots was found just below the root zone (around 120 cm depth). This NO3-N moved about 1 m deeper into the profile in response to the large winter precipitation observed during the 2017 spring. In contrast, the sandier flood treatment plot showed a reduction in soil NO3-N throughout the profile leaving a residual soil nitrate concentration of about 4-8 ppm NO3-N behind.

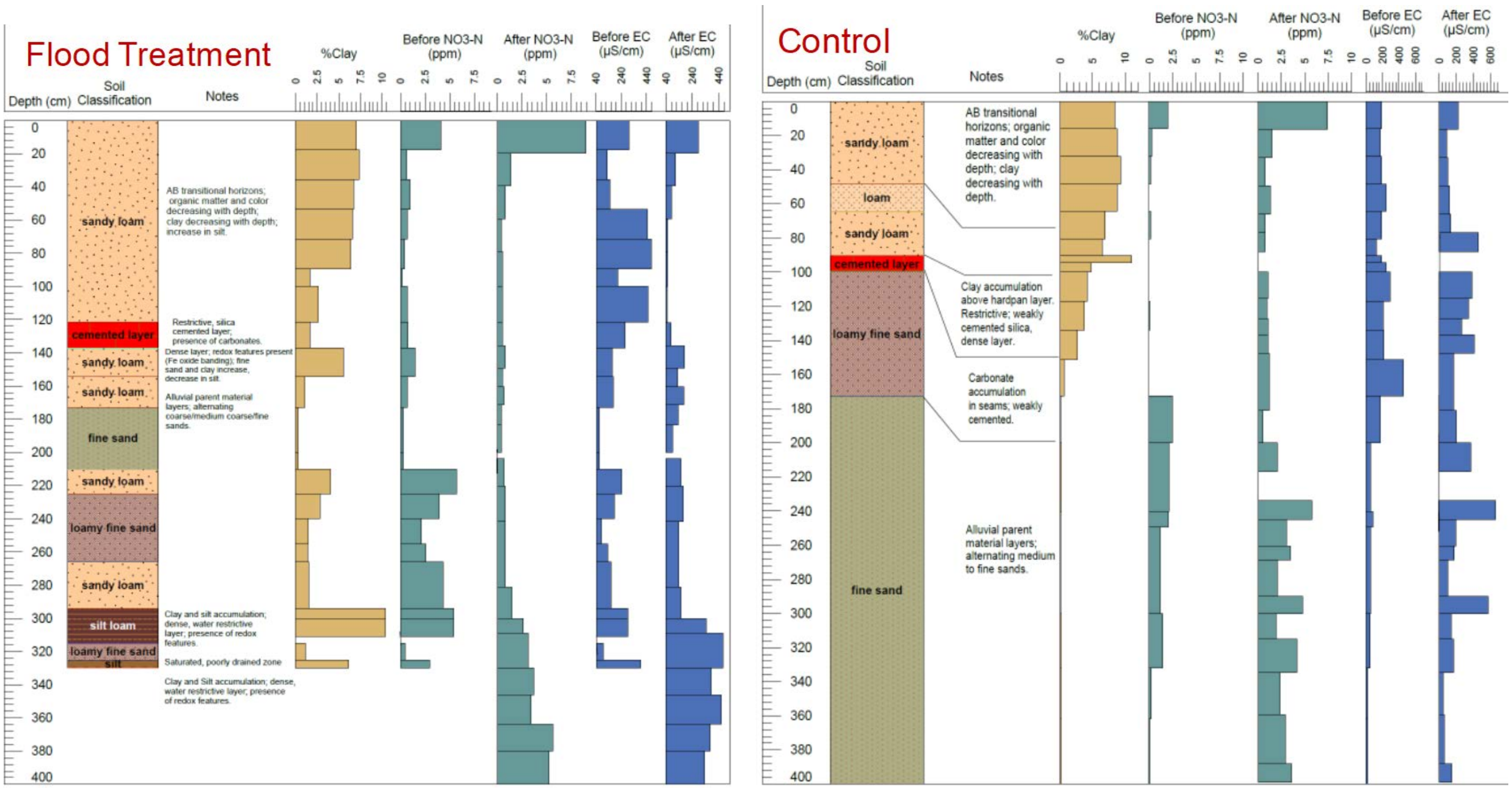

Figure 11: Soil stratigraphy, percent clay content, soil nitrate-N concentration, and electrical conductivity (EC) before and after winter recharge events in the flood and control treatment at the Modesto site for the 2015/16 season.

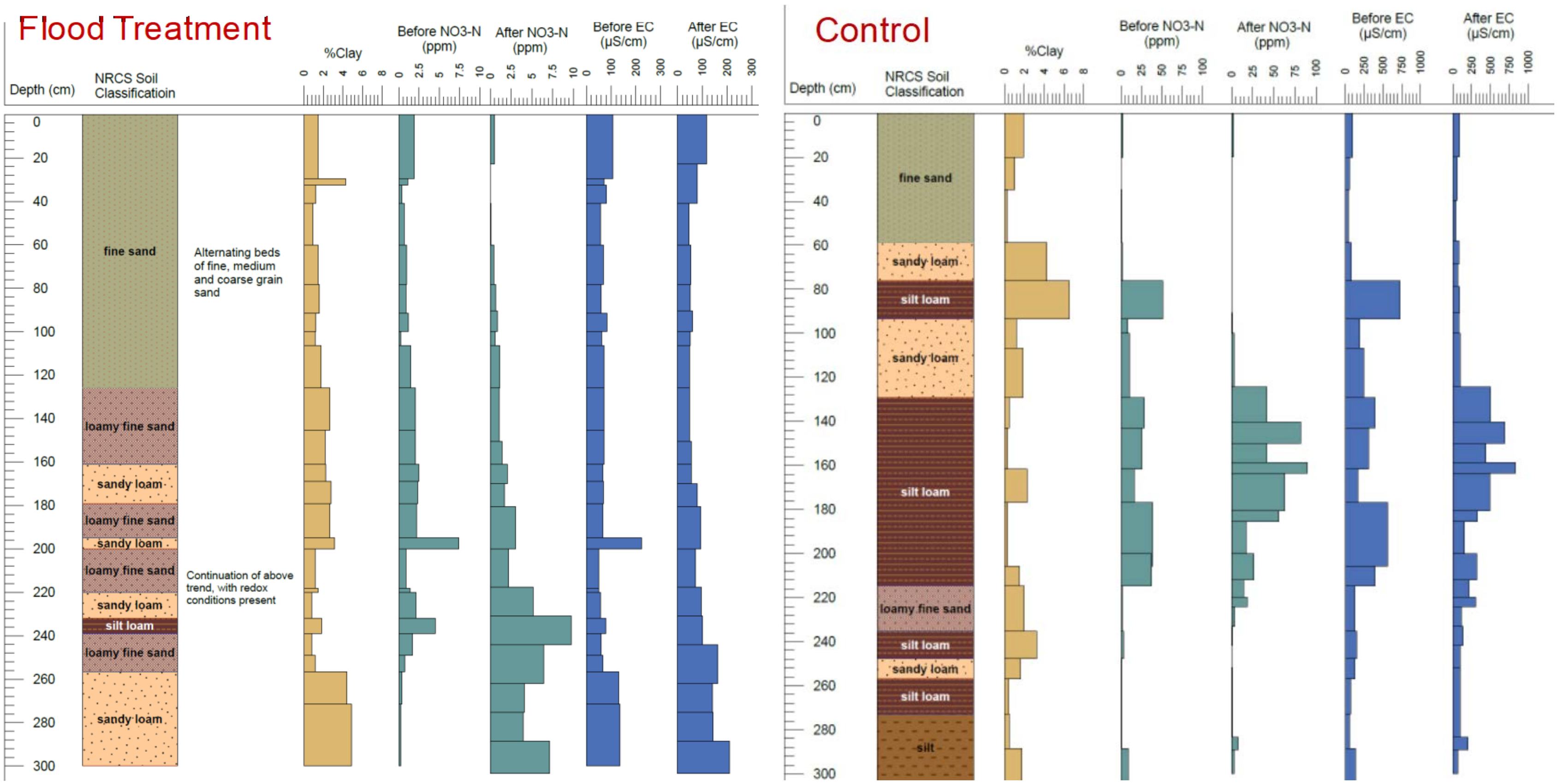

Figure 12: Soil stratigraphy, percent clay content, soil nitrate-N concentration, and electrical conductivity (EC) before and after winter recharge events in the flood and control treatment at the Delhi site for the 2015/16 season.

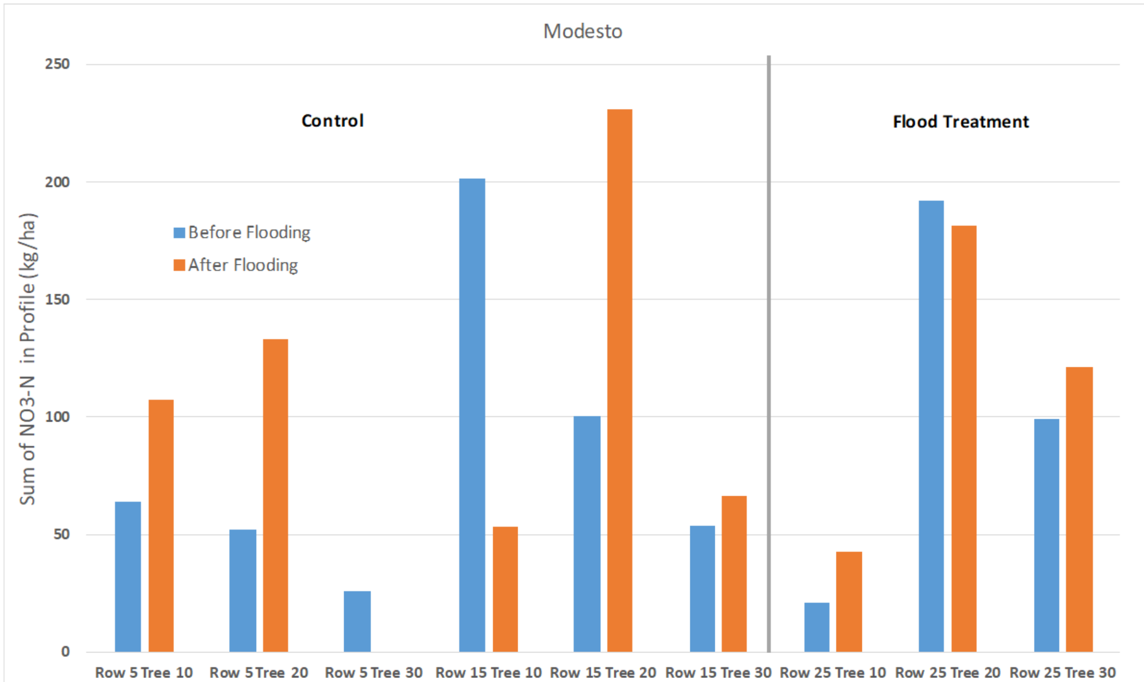

Figure 13: Total NO_3-N estimated over the entire core length (kg/ha) for the Modesto site for season 2015/16. Note, 1 kg/ha = 0.89 lbs/acre and $NO_3^- = NO_3^-$-N*4.43.

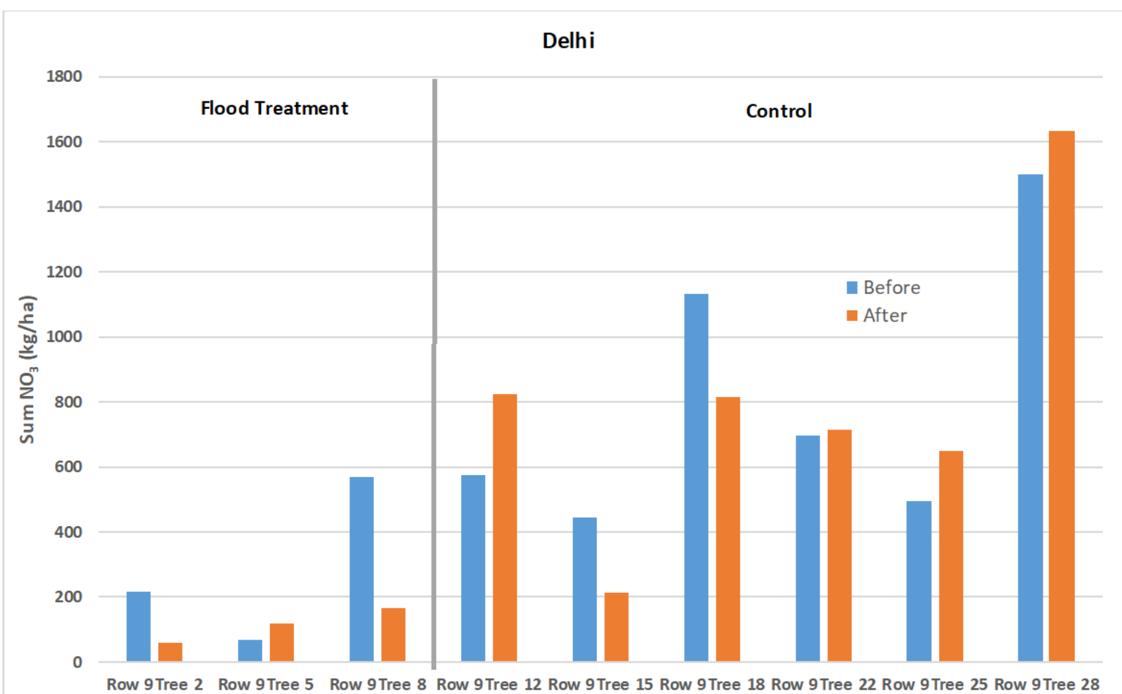

Figure 14: Total NO_3-N estimated over the entire core length (kg/ha) for the Delhi site for season 2015/16. Note, 1 kg/ha = 0.89 lbs/acre and $NO_3^- = NO_3^-$-N*4.43.

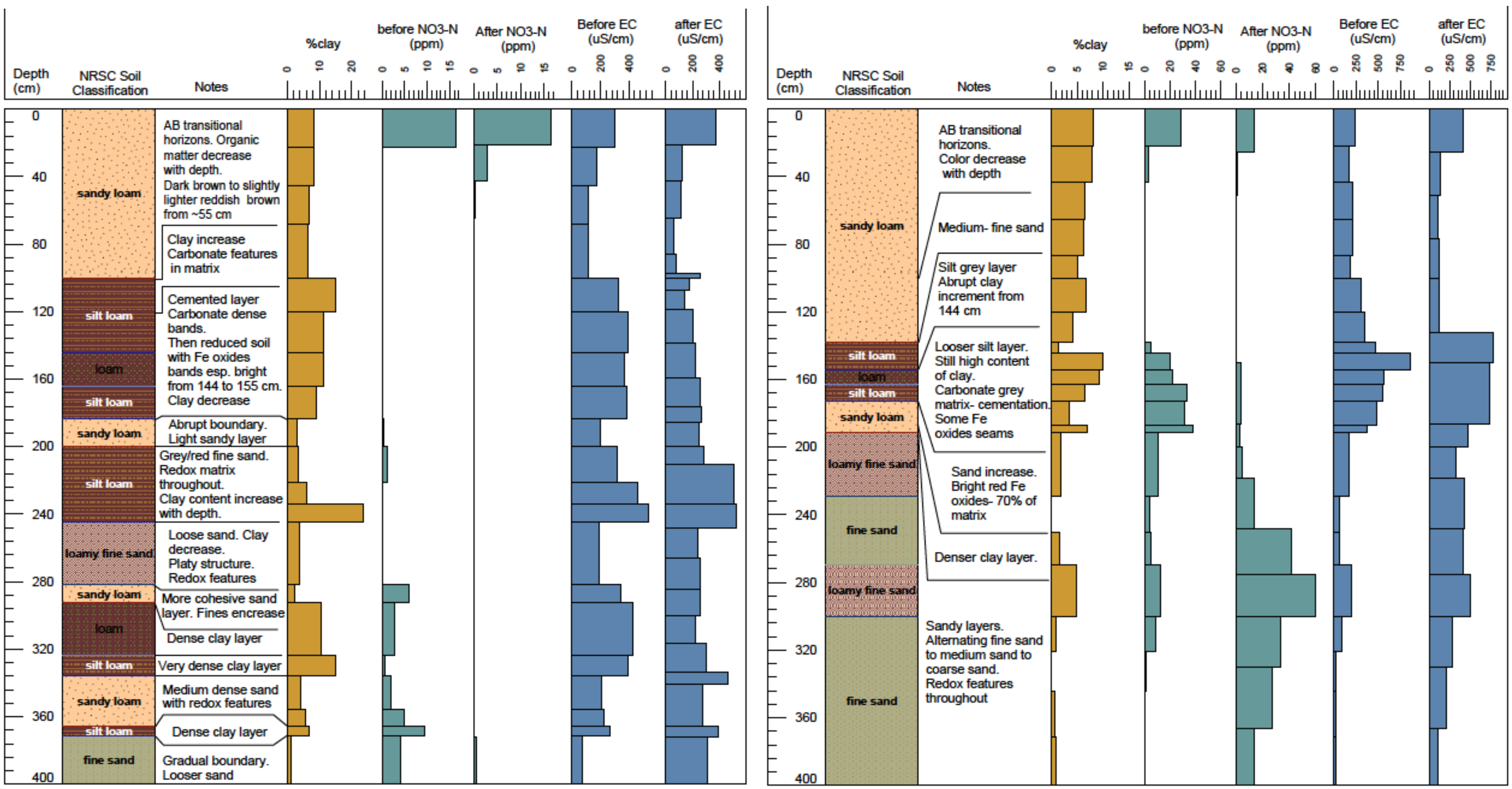

Figure 15: Soil stratigraphy, percent clay content, soil nitrate-N concentration, and electrical conductivity (EC) before and after winter recharge events in the flood (left) and control (right) treatment at the Modesto site for the 2016/17 season.

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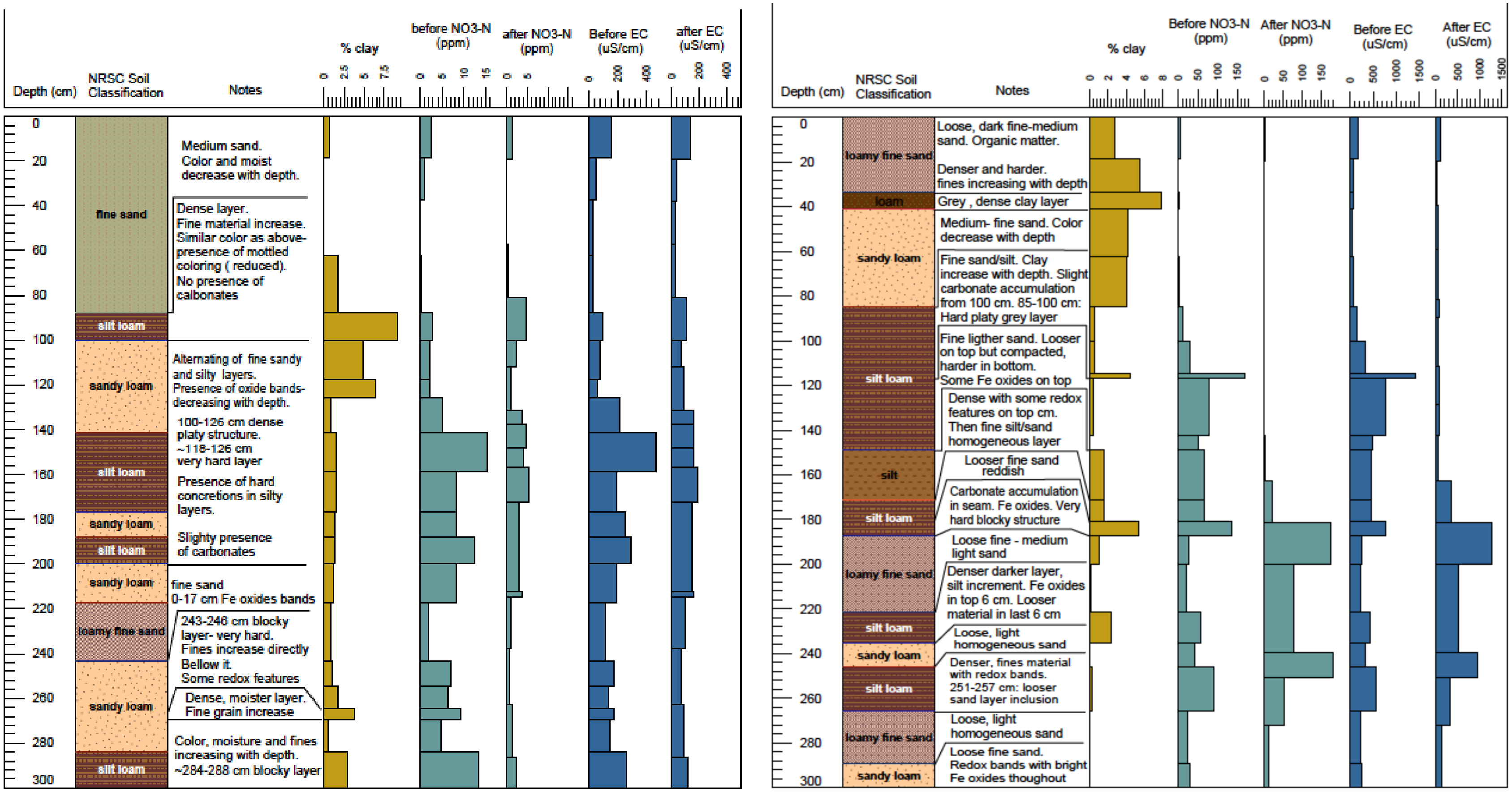

Figure 16: Soil stratigraphy, percent clay content, soil nitrate-N concentration, and electrical conductivity (EC) before and after winter recharge events in the flood (left) and control (right) treatment at the Delhi site for the 2016/17 season

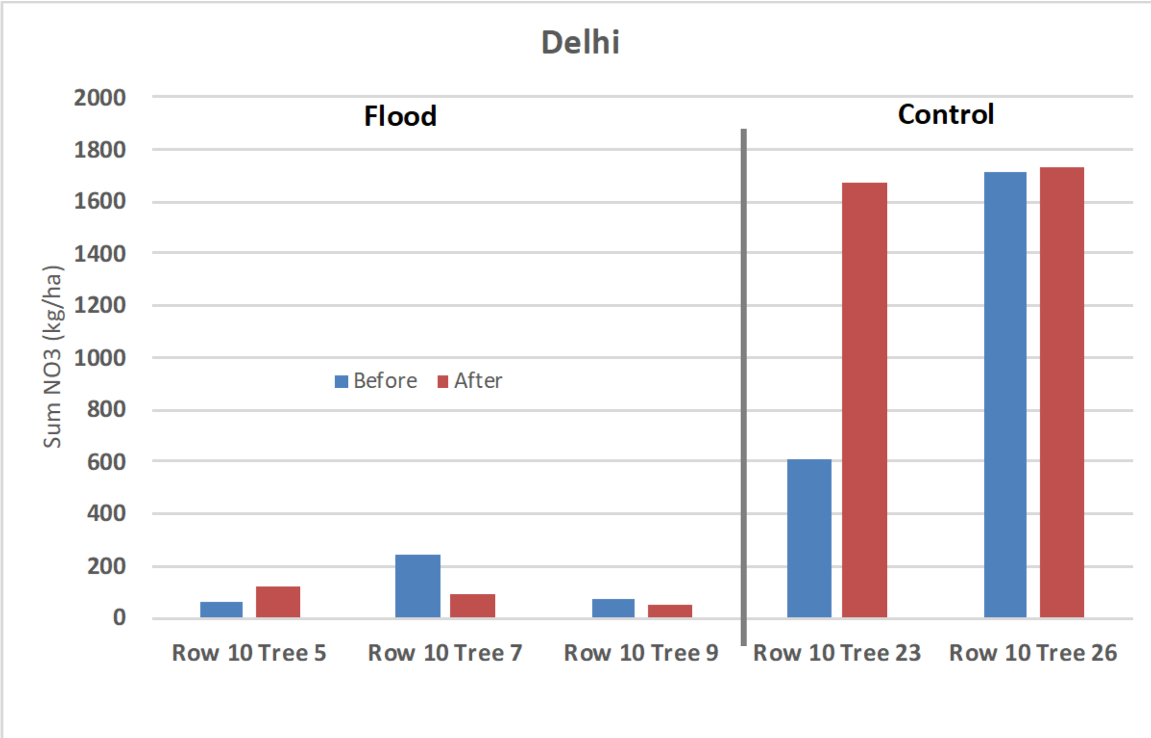

Figure 17: Total NO_3-N estimated over the entire core length (kg/ha) for the Delhi site for season 2016/17. Note, 1 kg/ha = 0.89 lbs/acre and $\boldsymbol{NO_3^-} = \boldsymbol{NO_3^-}$-*N*4.43.*

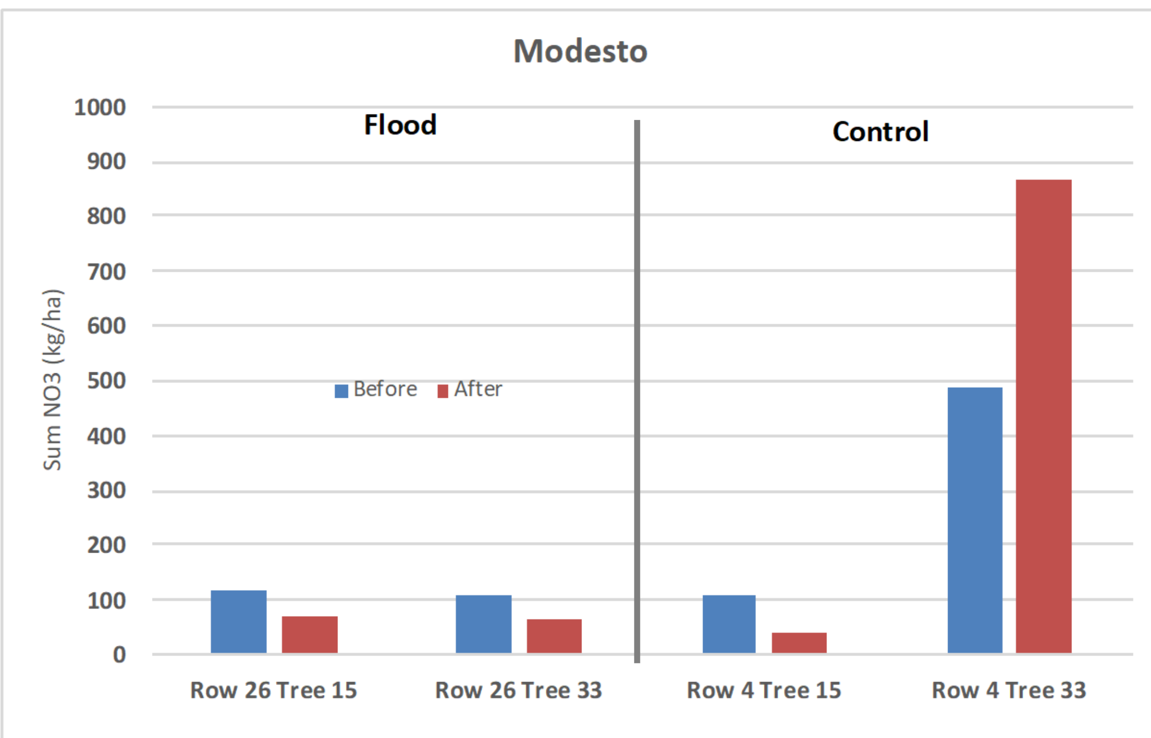

Figure 18: Total NO_3-N estimated over the entire core length (kg/ha) for the Modesto site for season 2016/17. Note, 1 kg/ha = 0.89 lbs/acre and $\boldsymbol{NO_3^-} = \boldsymbol{NO_3^-}$-*N*4.43.*

Treatment impact on stem water potential, light interception and yield

Tree stem water potential was not different between the trees exposed to recharge and those in the control treatment in either year at Delhi and Modesto (**Figure 19**). At both the Modesto and Delhi sites the treatments were not replicated, making a statistically sound comparison of tree responses to the treatments not possible, as other confounding factors such as differences in soil texture could also explain differences in responses or a lack of response.

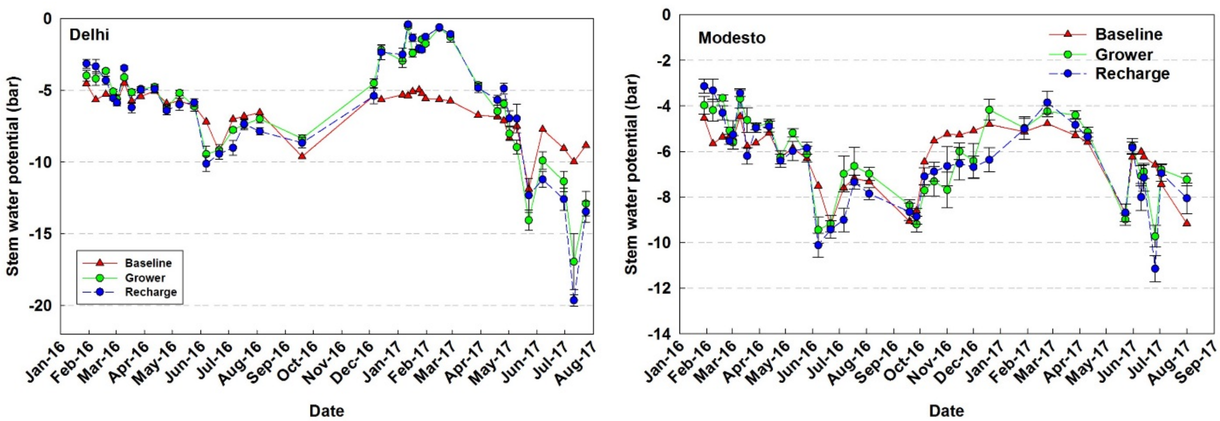

Figure 19. Stem water potential at Delhi following application of recharge water in Dec 15/Jan 16 and Dec 16/Jan 17. The impact of excessive winter rainfall in 2017 is clearly visible as trees were above the baseline for a prolonged period of time

At Orland we did have three blocks which allows for statistical comparison. During the first year were only able to add an additional 4.77 inches of water above the very large amount of winter rainfall the site already received. This did not have a statistical impact on stem water potential in the growing season (**Figure 20**).

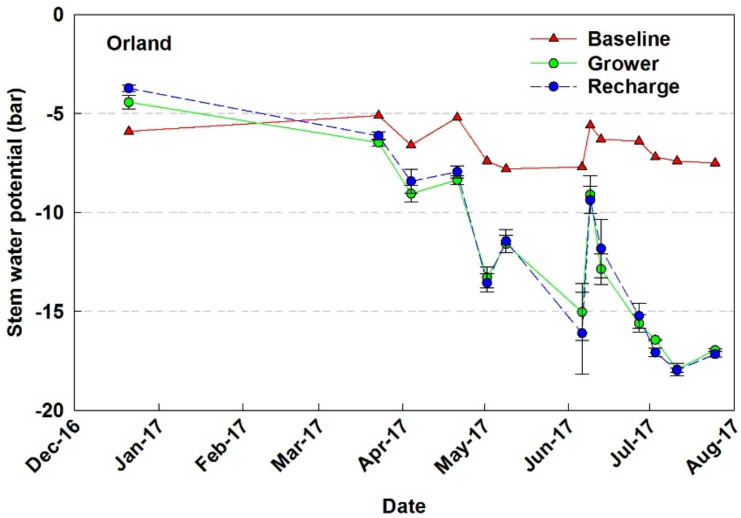

Figure 20. Stem water potential of trees receiving the grower treatment (natural rainfall) or an additional 4.77 inches of water in January 2017.

Canopy light interception and yield numbers at Modesto and Delhi in 2015 and 2016 were not obviously affected by applying winter recharge (**Tables 4 and 5**).

Table 4. Canopy light interception (%) within each treatment at the three sites. There was no statistical difference between treatments or year within each site

	2016		2017	
Site:	Control	Recharge	Control	Recharge
Modesto	88.8	85.2	75.1	77.2
Delhi	72.0	75.8	65.3	65.4
Orland	-	-	50.4	51.0

Table 5. Yield data for Modesto and Delhi prior (2015) and after (2016) treatment application

		Year	
Site	Treatment	2015 (pre-treatment)	2016
Modesto	Grower	3220	3090
	Recharge	3430	3130
	Grower - 2	3360	3290
Delhi	Grower	1230	1250
	Recharge	1410	1200

	Grower - 2	1190	1140

Treatment impact on new root length production and root lifespan

At the Delhi site, images have been processed through May 2017 for all tubes, whereas at Modesto only the grower treatment has been processed. Production data suggest there was no negative impact of winter recharge on new root production, although for the root data we also have the same replication caveat as for the stem water potential data.

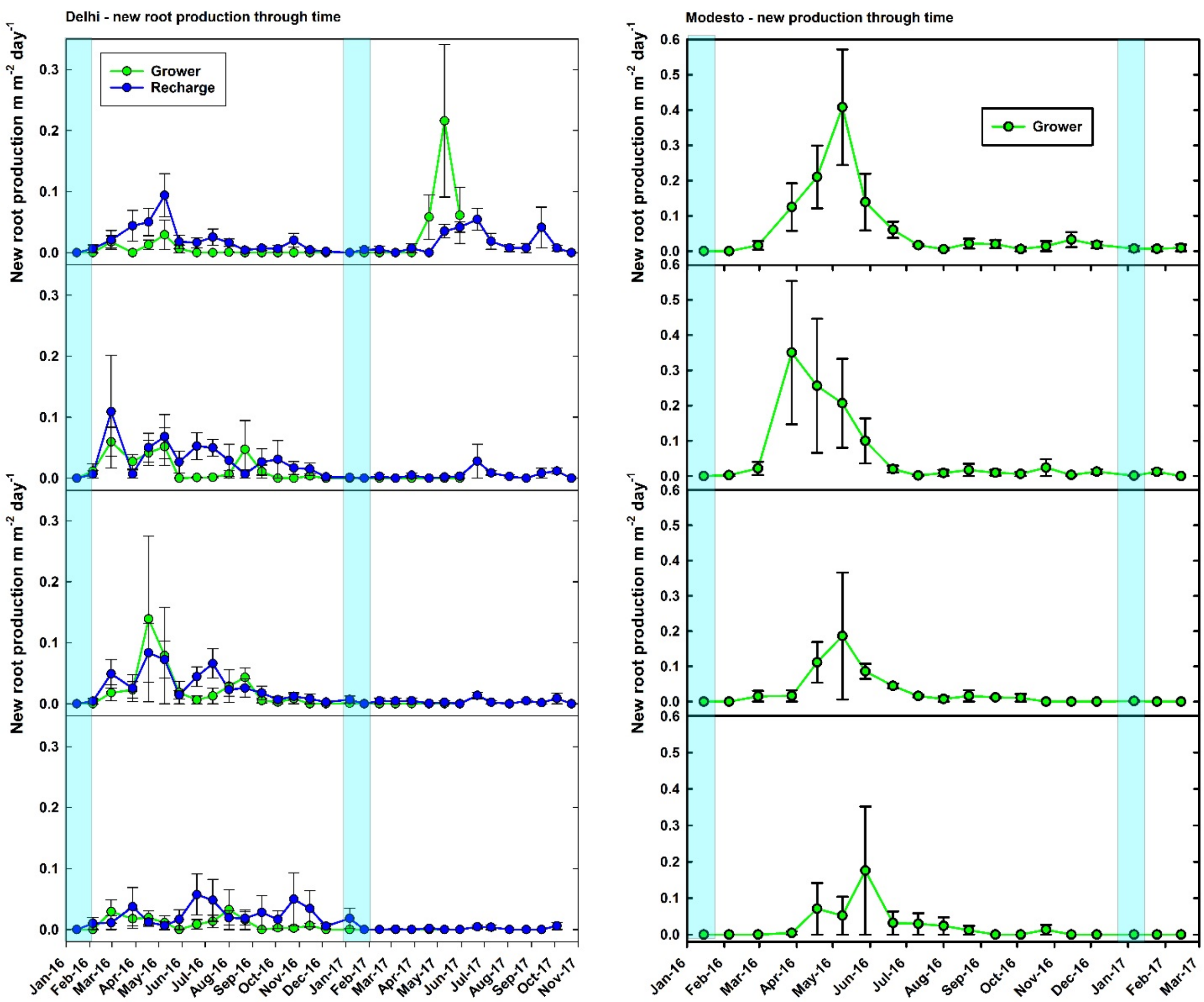

Figure 21. New root length production through time at four depths at Delhi and Modesto starting immediately after the first recharge event (Jan 16) and including the 2nd recharge event Dec/Jan 17. Currently all data for Delhi have been fully processed, except for a final data quality check on the 2017 April – Nov grower data. Data from Modesto and Orland are 25% processed.

Impact of winter irrigation during drought conditions
A pot study to determine the impact of drought during dormancy indicated that severe stress (SWP lower than -10 bar (**Figure 22**), more stressed than any winter field observation thus far) followed by irrigation prior to bloom, delayed bloom. Water stress treatments caused a delay in bloom, with a longer delay associated with higher stress and longer period of stress (**Figure 23**). However, the rate of bloom development was similar once bloom began in each treatment. The final flowering percentage was only significantly decreased for the treatment with the highest stress for the longest time. Additionally, none of the delayed flowers exhibited anatomical abnormalities, with fruits forming on all trees and kernels developing normally (data not shown)

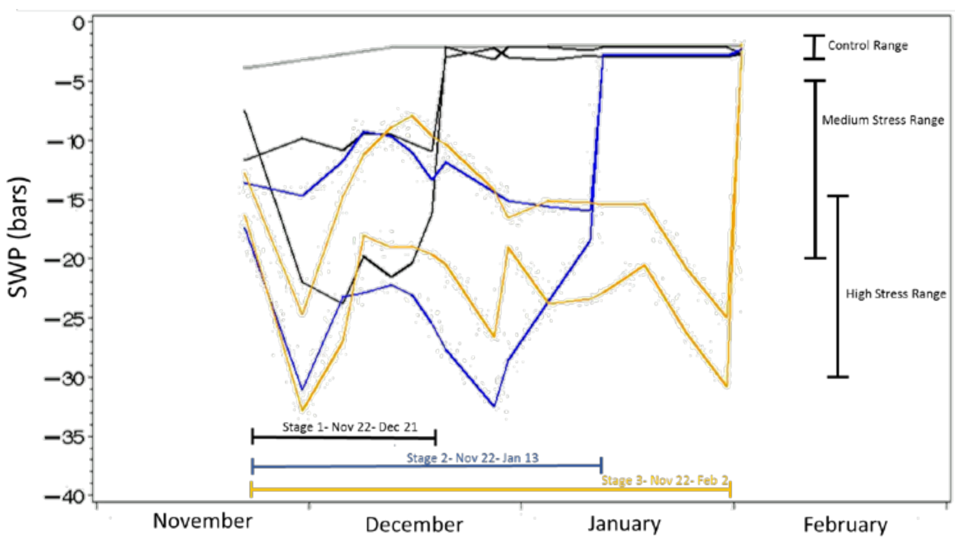

Figure 22. Treatment mean stem water potential (SWP) over time. Two stress level ranges and times (stages) were established. Error bars indicate the range for each stress level and control.

On November 22, 2016, the SWP values had dropped to desired levels and the drought stress treatments were considered begun. The dormant period was then divided into three time periods (stages). State 1 trees were irrigated (i.e., stress was removed) on Dec. 22, stage 2 trees on Jan. 13, and stage 3 trees on Feb. 2. Irrigated control trees had uniform and stable SWP values over time in the range of -1 to -3 bars, whereas trees in the stress treatments showed more variability both between trees and over time, ranging from -5 to -20 bars in the medium stress treatment and -15 to -30 bars in the high stress treatment (**Figure 22**).

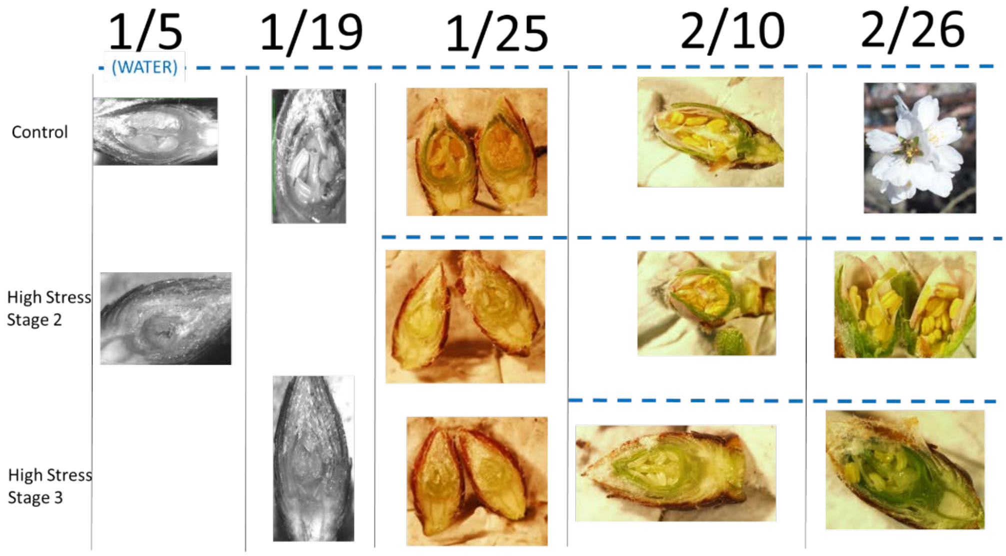

Figure 23. Cross sections of flower buds from different treatments, blue line indicates when trees were irrigated (stress was removed).

Evidence of a delay in flower bud development was seen in early January, with easily identifiable anthers and pistils present in the controls but not the high stress treatments on 1/5 and 1/19 (**Figure 23**). Microscopy of dormant flower buds showed delayed development in high stress treatments (**Figure 23**) and bud swell was also delayed in high stress treatments (data not shown). These results show promising insight into the effects of dormant drought stress on flower bud development and will be done much more extensively in 2017/2018 in order to better document the response of dormant flower bud development to winter drought stress.

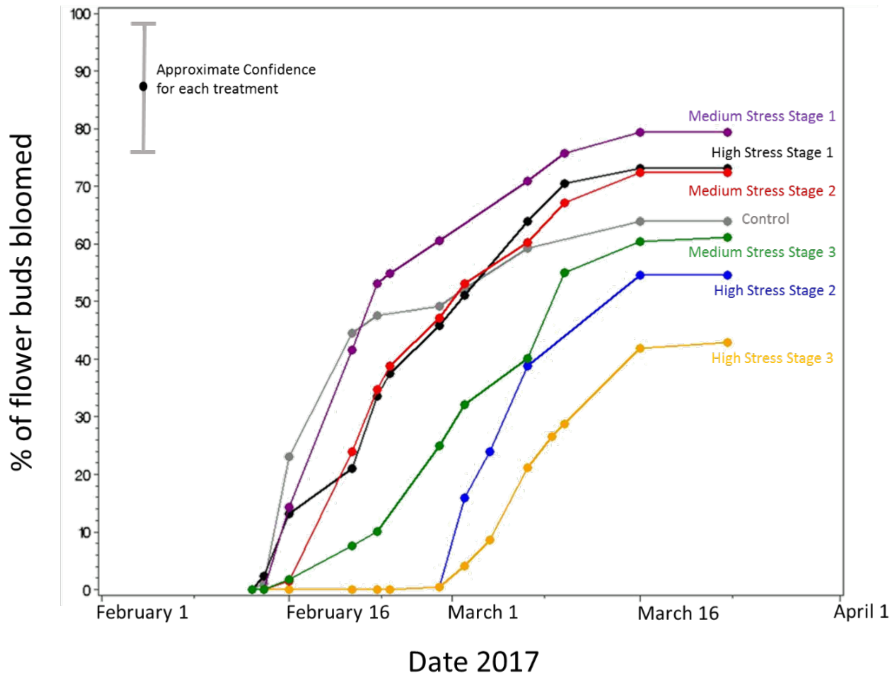

Figure 24. Treatment means of flower bud bloom percentage over time.

Water stress treatments caused a delay in bloom, with a longer delay associated with higher stress and longer period of stress (**Figure 24**). However, the rate of bloom development was similar once bloom began in each treatment. The final flowering percentage was only significantly decreased for the treatment with the highest stress for the longest time. Additionally, none of the delayed flowers exhibited anatomical abnormalities, with fruits forming on all trees and kernels developing normally (data not shown).

To better quantify the stress each tree experienced, analysis was done using a combination of stress level and duration, bardays. For example, a tree that had a -2 bar stress for 70 days would have a bardays of -140, a tree with an average stress of -20 bars for 70 days would have a -1400 bardays, and a tree with an average stress of -20 bars for 30 days that was then irrigated and recovered to a -2 bar stress for 40 days would have a –680 bardays.

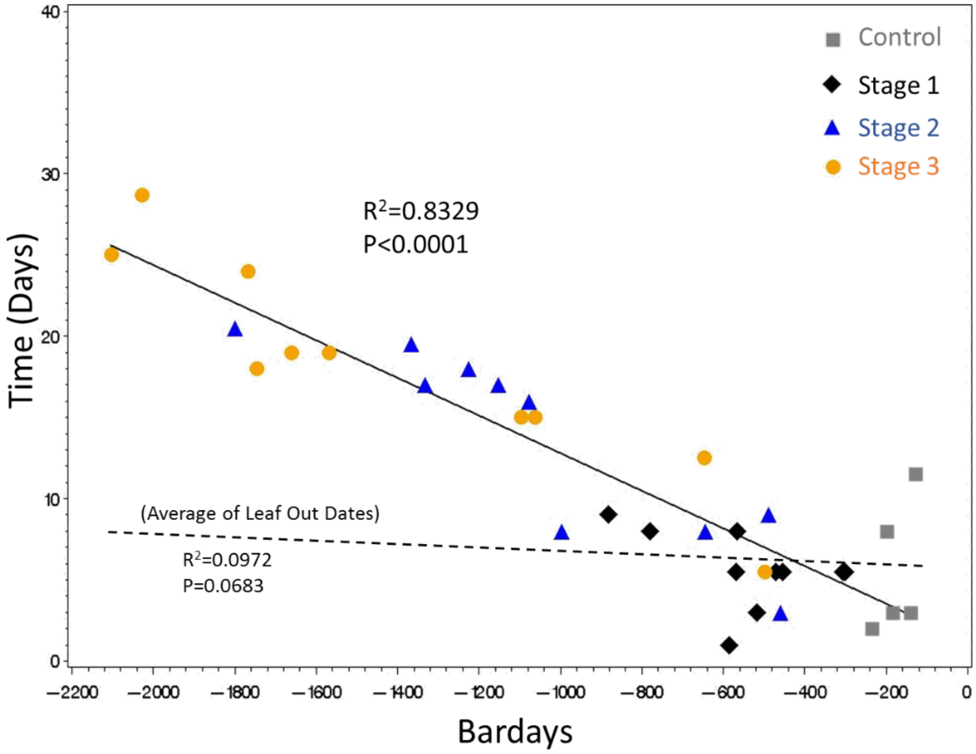

Figure 25. The dates of first bloom and leaf out plotted against bardays. Dates of first bloom had a range of ~28 days yet leaf out dates (dashed line) had a range of ~ 7 days

Dormant drought stress caused a significant delay in date of first bloom but did not have a significant effect on leaf out date. Dates of first bloom had a range of ~28 days and these delays were strongly significant ($p<0.0001$) with a decrease in bardays (**Figure 25)**. Leaf out dates had a range of ~ 7 days and were not significantly affected ($p=0.0683$) by a decrease in bardays (**Figure 25, dashed line)**.

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