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Title

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Permalink

https://escholarship.org/uc/item/8jh821jj

Journal

California Agriculture, 76(2-3)

ISSN

0008-0845

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Publication Date

2022

DOI

10.3733/ca.2022a0008

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RESEARCH ARTICLE

Winter flooding recharges groundwater in almond orchards with limited effects on root dynamics and yield

Almond orchards on soils with moderately high SAGBI or better can likely be used for winter water recharge with minimal negative effects and potentially some horticultural benefits.

by Xiaochi Ma, Helen Dahlke, Roger Duncan, David Doll, Paul Martinez, Bruce Lampinen and Astrid Volder

Online: https://doi.org/10.3733/ca.2022a0008

Abstract

California signed the Sustainable Groundwater Management Act (SGMA) into law in 2014. SGMA requires groundwater-dependent regions to halt overdraft and develop plans to reach an annual balance of pumping and recharge. Groundwater aquifers can be recharged by flooding agricultural fields when fallow, but this has not been an option for perennial crops such as fruit and nut trees. While flooding these crops might be possible during the dormant season, it is not known what impact flooding might have on tree-root systems, health and yield. We followed root production, tree water status and yield in two almond orchards in Northern California for 2 years to test the impact of applying captured winter water runoff for groundwater recharge purposes on tree performance. Results showed that more than 90% of the water applied to sandy soil and 80% of the water applied to loamy soil percolated past the root zones, with no measured adverse effects on tree water status, canopy development or yield. Groundwater recharge did not negatively affect new root production and tended to extend root lifespan. Based upon these data, applying additional water in late December and January is not likely to have negative impacts on almond orchards in moderately drained to well-drained soils.

Almond (*Prunus* spp.) is one of the top producing commodities in California; in 2019, almonds provided producers with cash receipts of $6.09 billion (CDFA 2020). From 2010 to 2019, almond acreage in the state increased by 79%; acreage of trees 4 years and older — called bearing acres — increased by 53%. During the same period, total California almond production increased by 55%, with an approximate value increase of $3.2 billion (CDFA 2020).

The expansion of almond orchards has increased irrigation demand in areas that rely heavily on groundwater reserves. In spite of some high water years (2017, 2019), the 10-year trend (2010–2020) shows that 28.4% of monitored wells had a water level decrease of 5 to 25 feet and 9.6% of monitored wells decreased by more than 25 feet. Over that same period, 14.8% of wells showed an increase in groundwater level (CADWR 2019). Groundwater decreases are particularly pronounced in the Tulare Lake, San Joaquin River and Sacramento River hydrologic regions (the whole Central Valley). In an effort to reduce groundwater overdraft, California signed the Sustainable Groundwater Management Act (SGMA) into law in

Results from a 2-year study suggest that applying winter runoff to Central Valley orchards in moderately drained to well-drained soils has minimal effects on yield, root production and light interception. *Photo*: David Doll.

2014. SGMA requires groundwater-dependent regions to combat the drop in groundwater levels by developing plans to balance pumping and recharge.

One promising approach in this effort is to transfer surplus surface water into groundwater aquifers during winter on agricultural lands (O'Geen et al. 2015). While this practice is relatively easy with annual crops that have a fallow period, this option has not been widely explored yet with perennial crops, in part due to concerns that prolonged soil saturation may damage crop root systems. A recent study on alfalfa in California demonstrated the feasibility of this approach in highly permeable soils (Dahlke et al. 2018). The large acreage of California's almond orchards and the available water distribution infrastructure used to support it could potentially facilitate groundwater reservoir recharging in these orchards during winter, but it is not known what potential effects flooding might have on the trees' aboveground growth and production. It is also not known what effect flooding might have on the trees' root systems. In particular, there may be concerns with exposing the perennial roots to potentially damaging low-oxygen conditions when orchards are kept saturated (Kozlowski 1997). Responses of roots to groundwater recharge are important because roots play a vital role in water and nutrient uptake (Osmont et al. 2007). They also function as anchors and storage organs, providing carbohydrates to restart aboveground development after the dormancy period ends (Tixier et al. 2019).

To evaluate the impact of winter flooding on almond root growth, canopy development, whole-plant water status and yield, we conducted field experiments in two commercial almond orchards in California's Central Valley, one with highly permeable soil and one with moderately permeable soil. Because our recharge treatments occurred during the dormant season, we hypothesized that almond trees would be able to tolerate saturated or nearly saturated soil conditions during this period without negative effects on root growth, water status or yield. In California, there are over 5 million acres of soils with Agricultural Groundwater Banking Index (SAGBI) ratings of excellent, good and moderately good (O'Geen et al. 2015). Most of these soils are on the east side of the Central Valley; the findings from this study will benefit those areas, with implications for the practice of groundwater recharge in dormant orchards.

Experimental sites and design

We conducted field experiments simultaneously in two almond orchards, one near Delhi, the other near Modesto (fig. 1), from December 2015 to October 2017. The orchard near Delhi (37 24'16 N, 120 47'20 W) was established in 2000 with alternating rows of Butte and Padre varieties on Nemaguard rootstock. Trees are spaced 18 feet apart with 22 feet between rows. The soil type at this site is Dune Sand with a SAGBI rating of "excellent". The second orchard, near Modesto in Stanislaus County (37 36'30 N, 121 04'20 W), was established in 1996 with alternating rows of 50% Nonpareil and 25% each of Monterey and Sonora varieties on Nemaguard rootstock. Trees are spaced 21 feet apart with 22 feet between rows. The soil in this orchard is classified as Dinuba Fine Sandy Loam, with a SAGBI rating of "moderately good" (O'Geen et al. 2015). Soil stratigraphy at each field site is illustrated in the online technical appendix. We obtained precipitation data from stations #71 Modesto and #206 Denair II of the California Irrigation Management and Information System (CIMIS; https://cimis.water.ca.gov).

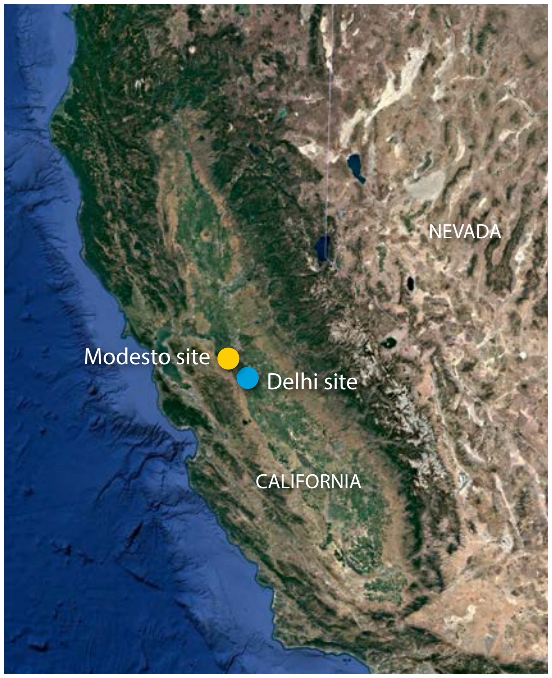

FIG. 1. Location of field sites in Delhi (Merced County) and Modesto (Stanislaus County), California. *Image:* Google Earth.

Capturing stormwater runoff and potentially banking it in groundwater through winter irrigation in almond orchards might be a feasible method to reduce groundwater overdraft in California.

At each site, we applied recharge and control treatments to different sections of the same orchard block. At Modesto during the growing season the orchard is basin flood–irrigated approximately every 3 weeks using surface water provided by the local irrigation district. During January 2016 and January 2017, we applied 6 inches of water weekly (a total of 24 inches each month) to nine contiguous recharge treatment rows via flood irrigation, using city stormwater runoff captured by the Modesto Irrigation District and rerouted to irrigation canals. We measured root dynamics and stem water potential in five randomly selected trees from three center Nonpareil rows, and we measured yield and light interception for all Nonpareil trees in the treatment block.

At Delhi, we chose five rows, each with 32 trees (alternating Butte/Padre), for our experiment. During the active growing season, the grower irrigates these rows using micro-sprinkler irrigation. During our study, from December 2015 to mid-January 2016 and again during January 2017, we applied 8 inches of water to the first 10 trees in each row in three separate events (24 inches total per season) via flood irrigation with pumped up local groundwater. We used the last 12 trees in each row for control measurements. As in the Modesto orchard, we measured root dynamics, stem water potential, yield and light interception on five randomly selected trees; we selected trees for this purpose from the center row (Butte). Dates and amounts of groundwater recharge events in both sites are shown in table 1.

Measurements and data analyses

During our 2-year study, we measured soil water content for each treatment at each experimental site at 10-minute intervals at depths of 6 inches, 18 inches and 40 inches using GS3 soil-moisture sensors (Decagon Devices, Pullman, Wash.). We measured stem water potential (Ψ_{stem}) of bagged leaves in the active growing season and twigs in the dormant season bi-weekly. We measured root-growth dynamics from minirhizotron root images that we collected every 3 weeks using a portable CID root imager (CID Bio-Science, Camas, Wash.). (We installed clear root observation tubes to a 2-foot soil depth at an angle of 60° and inserted swimming pool noodles to prevent temperature gradients. We capped and covered the tubes with sand-filled bags to prevent them from flooding and/or floating away.) We hand-traced roots in the images using RootFly software (Clemson University), and from the tracings we calculated total lengths of new roots and of disappeared/dead roots through time. We measured canopy light interception (i.e., photosynthetically active radiation below the canopy) during the growing seasons in 2016 and 2017 using methods described in Zarate-Valdez et al. (2015). We measured yield at harvest in 2015 (pre-treatment) and again in 2016 and 2017. We used a t-test to determine whether there was a significant difference between the means of two treatment groups at a significance level of $P = 0.05$. More details on measurements and data calculation can be found in the technical appendix.

TABLE 1. Dates of groundwater recharge events and amount of applied water for each event during the winters of 2015–2016 and 2016–2017 at Delhi and Modesto

	Delhi		Modesto	
Season	Date	Irrigation amount	Date	Irrigation amount
		inches		*inches*
2015–2016	12/23/15	8	1/4/16	6
	12/29/15	8	1/11/16	6
	1/12/16	8	1/19/16	6
			1/25/16	6
2016–2017	1/13/17	8	1/9/17	6
	1/19/17	8	1/16/17	6
	1/26/17	8	1/23/17	6
			1/30/17	6

Soil water content in response to winter watering

We observed that the deep percolation rate of applied water in the sandy soil of Delhi was higher than the deep percolation rate in the sandy loam soil at Modesto (table 2). This suggests that soil permeability is one of the major factors determining the efficiency of groundwater recharge in winter. Natural precipitation during the second season of our study (October 2016 to April 2017) was significantly higher than it was during the first season at both Delhi (35% increase) and Modesto (26% increase) (table 2). This explains the greater deep percolation rate of applied water in both sites in 2017 compared to 2016 (6% and 15% increases at Delhi and Modesto, respectively).

Soil moisture sensors in Modesto showed that soil water content at this site depleted more quickly in deep soil (at 3.3-foot depth) than in shallow soil (at 0.5-foot

TABLE 2. Water inputs (precipitation and applied water for groundwater recharge) and estimated deep percolation and loss of applied water to soil storage from October to April of 2015–2016 and 2016–2017 at Delhi and Modesto

Site	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*	*percentage*	*inches*	*percentage*
2016								
Delhi	12.94	26.15	29.09	4.79	24.31	93	1.84	7
Modesto	9.91	24.00	21.90	2.55	19.35	81	4.65	19
2017								
Delhi	17.44	25.80	33.03	7.43	25.60	99	0.20	1
Modesto	12.46	24.00	27.94	4.78	23.16	96	0.84	4

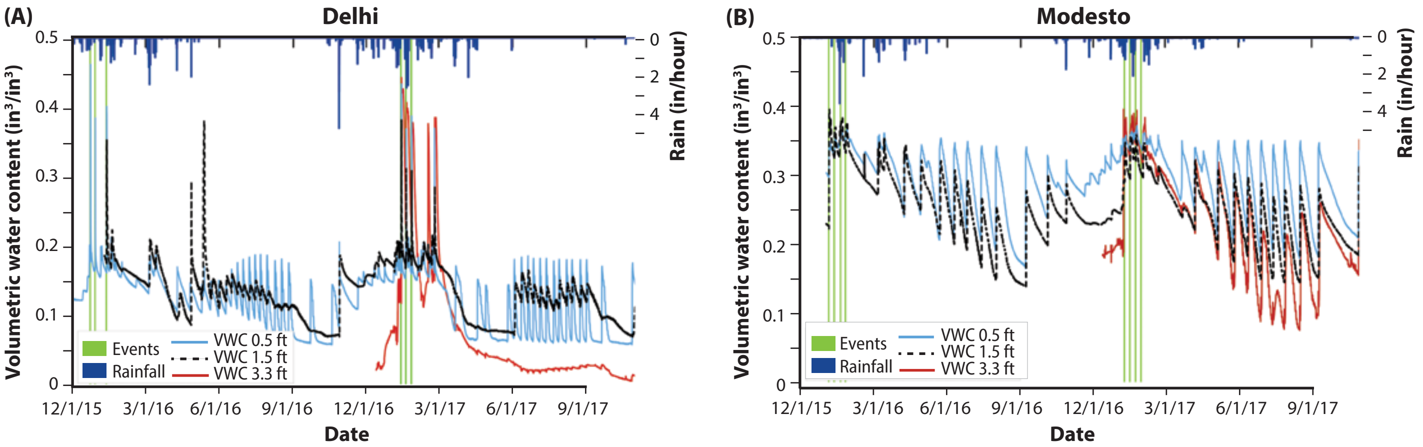

FIG. 2. Volumetric water content (VWC, in^3/in^3) for winter-watered almond orchards at (A) Delhi and (B) Modesto, measured at 0.5 ft (15 cm; blue solid lines), 1.5 ft (45 cm; black dashed lines) and 3.3 ft (100 cm; red solid lines). Blue bars represent the daily precipitation amount (inches/hour); green bars represent groundwater recharge events.

and 1.5-foot depths) at the beginning of 2017 (fig. 2), suggesting that, at Modesto, deeper layers have greater hydraulic conductivity (supplementary figs. 1 and 2 in the technical appendix).

Soil texture significantly influenced residence time of the water as well as deep percolation rates. Maximum soil water content at 1.5-foot depth after one recharge event was reached much more quickly in the sandy soil at Delhi (1 hour) than in the fine sandy loam at Modesto (more than 24 hours, fig. 3). Root-zone residence time (RZRT) of flood water, defined as the length of time it takes for soil water content to return to pre-flooding conditions after each event of groundwater recharge, was much longer at the Modesto site (6 inches of water applied per event, RZRT > 72 hours) than at the Delhi site (8 inches applied per event, RZRT < 24 hours).

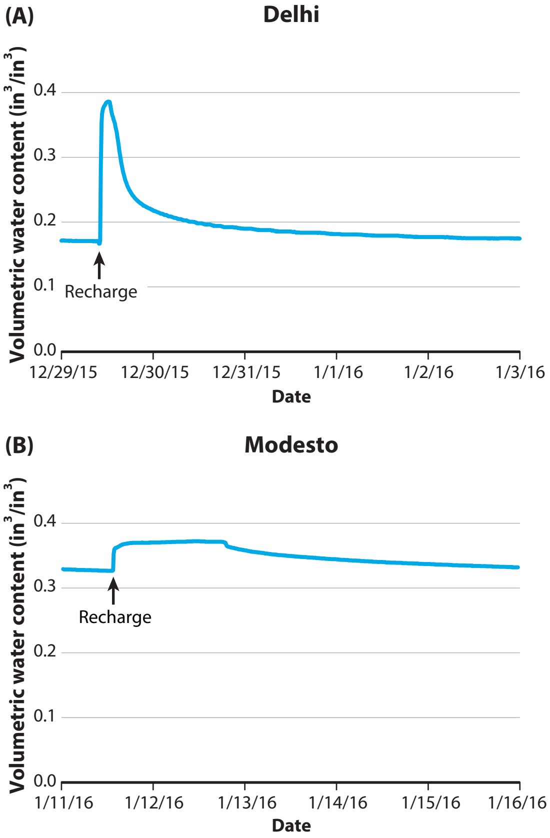

FIG. 3. Changes in volumetric water content (VWC, in^3/in^3) at 1.5 ft (45 cm) soil depth in response to a single flood event (black arrows) at (A) Delhi and (B) Modesto. During each groundwater recharge event, 8 inches of water were applied at Delhi, and 6 inches at Modesto.

Water status and root growth

We found no negative effects of groundwater recharge on tree water status. Ψ_{stem} during winter and in early spring was at or higher than the baseline for all trees at both field sites in both years (fig. 4). In both years the last winter groundwater recharge event took place in late January, and the introduced water stayed in the root zones no more than a week. At this time of year the trees have not leafed out yet and thus we would not expect any direct effects of water added on the physiology of the tree unless the tree was water stressed or the root system was negatively affected by saturated conditions in the root zone. We found no evidence of increased root death or decreased root production in the months immediately after the recharge events were applied in either year (table 3, January–March). However, in 2016 we found less negative in-season Ψ_{stem} for trees in plots where winter water for recharge was applied compared to the control (no extra water applied) at Delhi. This was likely due to other factors than the winter recharge treatment. At Delhi the recharge plots had a deeper layer of sandy soil in the recharge plot, which may have allowed deeper root growth under the high frequency summer irrigation regimen typical of orchards located on sandy soils.

Adding winter water for groundwater recharge showed no adverse effects on new root production at either site (tables 3 and 4). Almond trees produce most new roots around the stage of nut development, from April to June (see example in fig. 5). At Delhi, we found no significant increase in total length of new roots in winter-watered trees in the first months after

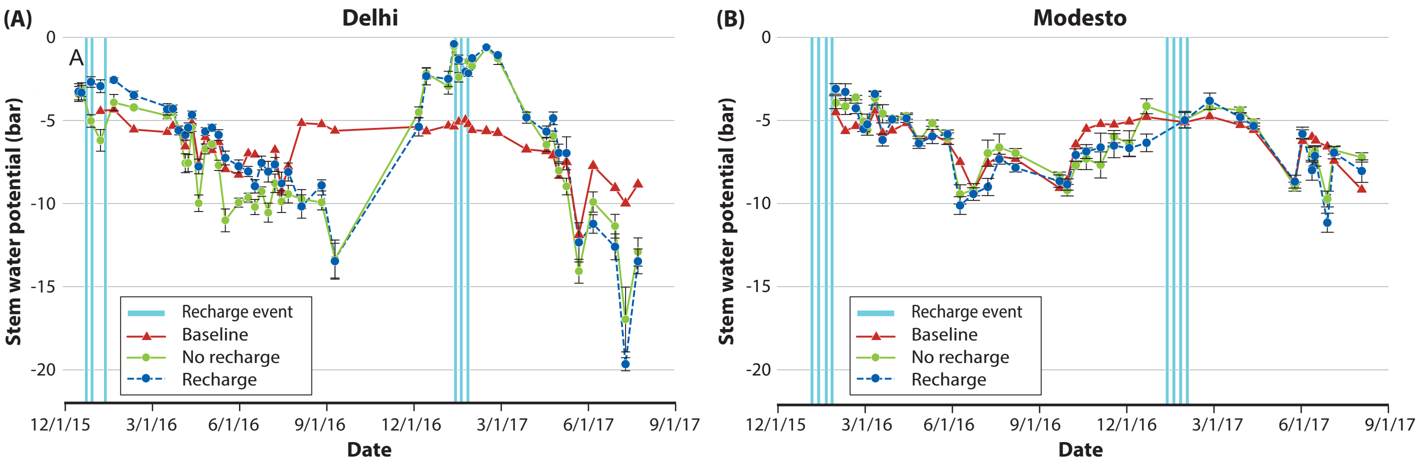

FIG. 4. Stem water potential (Ψ_{stem}, bar) of irrigated almond trees (blue circles) and nonirrigated trees (green circles) for winter groundwater recharge events in (A) Delhi and (B) Modesto in 2016–2017. Baseline (red triangle) was the expected water potential for well-watered trees based on weather conditions during the measurement period. Blue bars represent the events of groundwater recharge. Error bars represent standard error ($n = 5$).

TABLE 3. Seasonal changes in total lengths of new and dead roots at Delhi with and without winter groundwater recharge treatment

Year	Time period	Total length of new roots (*in/ft*$^2_{\textit{tube surface}}$)		Total length of dead roots (*in/ft*$^2_{\textit{tube surface}}$)	
		No recharge	Recharge	No recharge	Recharge
2016	January–March	6.99 ± 2.56	7.52 ± 3.81	0.56 ± 0.20	2.49 ± 2.13
	April–June	20.00 ± 11.57	13.08 ± 3.15	**7.52 ± 2.14**	**1.59 ± 0.69**
	July–September	8.08 ± 2.93	8.07 ± 2.87	1.95 ± 1.20	4.22 ± 1.62
	October–December	0.97 ± 0.40	4.70 ± 1.93	4.08 ± 2.98	2.31 ± 0.99
2017	January–March	2.10 ± 1.39	1.74 ± 1.02	4.98 ± 1.74	11.09 ± 4.43
	April–June	9.15 ± 4.49	3.97 ± 0.51	4.61 ± 1.59	8.17 ± 2.02
	July–September	5.63 ± 2.60	4.20 ± 2.01	8.89 ± 3.45	6.23 ± 1.26
	October	0.03 ± 0.03	0.60 ± 0.21	4.20 ± 1.22	3.72 ± 1.10

Numbers represent mean ± standard error; bold numbers indicate a statistically significant difference ($P < 0.05$) between treatments.

TABLE 4. Seasonal changes in total lengths of new and dead roots at Modesto with and without winter groundwater recharge treatment

Year	Time period	Total length of new roots (*in/ft*$^2_{\textit{tube surface}}$)		Total length of dead roots (*in/ft*$^2_{\textit{tube surface}}$)	
		No recharge	Recharge	No recharge	Recharge
2016	January–March	0.81 ± 0.51	4.84 ± 4.13	0.00 ± 0.00	0.00 ± 0.00
	April–June	12.90 ± 2.90	15.82 ± 5.16	3.29 ± 1.47	0.60 ± 0.30
	July–September	2.25 ± 0.50	3.21 ± 0.60	9.05 ± 2.63	3.86 ± 0.89
	October–December	0.93 ± 0.55	3.14 ± 0.83	1.87 ± 0.91	4.28 ± 1.22
2017	January–March	2.99 ± 0.84	3.86 ± 1.12	2.21 ± 0.67	4.96 ± 1.78
	April–June	4.47 ± 2.02	3.97 ± 0.35	3.06 ± 0.20	5.12 ± 0.79
	July–September	0.52 ± 0.26	0.90 ± 0.26	2.93 ± 1.45	5.29 ± 1.02
	October	0.19 ± 0.19	0.16 ± 0.05	0.82 ± 0.44	1.97 ± 0.65

Numbers represent mean ± standard error.

the recharge treatment was applied (January–March), yet there was a trend to lower April–June new root length production in the recharge treatment in both years (table 3). In the Modesto orchard, trees that received extra winter water showed a tendency to produce more new roots in the first quarter (January–March) of each treatment year (table 4), especially in 2016, which had low winter rainfall. These results indicate that winter irrigation does not have a statistically significant impact on root development in highly

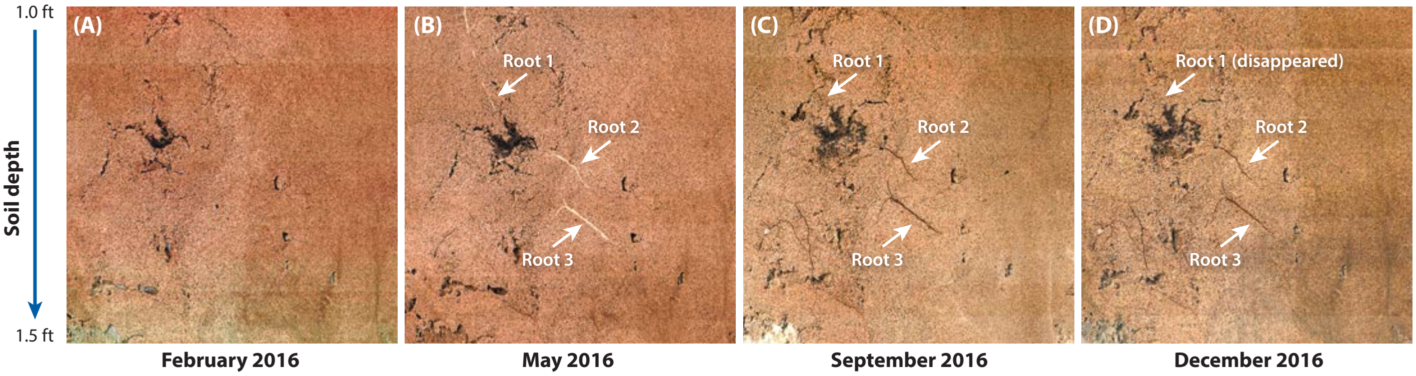

FIG. 5. An example of root growth dynamics at the Delhi site. Raw root images were taken at soil depths between 1 and 1.5 feet (30–45 cm) by using the CI-600 root imager (CID Bio-Science) in (A) February, (B) May, (C) September and (D) December of 2016. *Photos:* Paul Martinez.

permeable sandy soils or moderately permeable soils (e.g., sandy loam).

Standing root length is the net result of both new root length produced and root length that has died. When studying the impact of a treatment on root death, it is important to keep in mind that roots first need to be produced before they can die. Thus, a high root length that died can be either the result of high production in a previous month or the result of accelerated root death (reduced lifespan of produced roots). At Delhi, reduced length of dead roots in the recharge treatment in April–June 2016 reflects the lower new root production in that same period (keeping standing root length the same). In 2016 at Modesto, however, we had considerably higher new root length production through June in the recharge treatment but this was matched with much reduced dead root length production, thus suggesting that the lifespan of the roots was longer in the winter recharge plots. We did not find this in 2017. An extended lifespan reduces the ability of roots to take up water and soil nutrients (Volder et al. 2004). This pattern was not repeated in 2017, suggesting that variations in climate or soil conditions between the plots and years, not recharge treatments, could explain the results. Significantly higher precipitation in 2017 (table 2) increased soil water availability for root growth both in the control and in the treatment plots, thus minimizing any potential positive effects of winter irrigation.

Canopy light interception and yield

Groundwater recharge in winter showed minimal effects on canopy development and nut production; canopy light interception and yield were similar between treatments during each year at both field sites (table 5). Both sites had slight decreases in percentage of canopy light interception, indicating a reduced canopy size across treatments (with and without groundwater recharge) in the wet year of 2017 compared to the dry year of 2016. This is to be expected based on patterns of spur dynamics; more spurs die in a dry year, thus leading to reduced canopy size in the following year (Lampinen et al. 2011).

While annual yield at Modesto was fairly consistent over the two years of our study, we observed substantial annual variation in yield at Delhi. The year 2016 was a low-producing year in both winter-watered and control treatment blocks at Delhi, while 2017 was a higher-producing year, especially in the recharge treatment block (table 5). However, there was also greater yield in this same block in 2015, the year prior to the application of winter recharge (+46% and +41% greater production in the recharge block in 2015 and 2017, respectively). The higher yields in 2015 (pre-treatment) and 2017 in the recharge block at Delhi support the idea that trees there may have deeper root systems, which help maintain high nut production in the years following a dry year by enabling greater spur survival (Lampinen et al. 2011). At Delhi, the soil profiles between the recharge treatment and the control block were sufficiently

TABLE 5. Canopy light interception (%) and almond yield (lb/acre) for blocks grown with and without winter groundwater recharge at Delhi and Modesto in 2016 and 2017

	Canopy light interception *(%)*		Yield *(lb/acre)*					
	2016	2017	2015*	Percentage	2016	Percentage	2017	Percentage
Delhi								
No recharge	72.0	65.3	2,415	100.0	1,575	100.0	2,202	100.0
Recharge	75.8	65.4	3,535	146.0	1,393	88.0	3,108	141.0
Modesto								
No recharge	88.8	75.1	3,360	100.0	3,291	100.0	2,982	100.0
Recharge	85.2	77.2	3,425	102.0	3,129	95.0	2,985	100.0

* Results for 2015 reflect pre-experiment conditions.

different (see technical appendix) that this is a more likely explanation than the recharge treatment *per se*.

Thus, we found no positive or negative effect of adding water for winter recharge on yield at either Delhi or Modesto. It is possible that younger almond orchards (i.e., those less than 15 years old) might have different responses to winter recharge treatment, which is a possibility that needs to be investigated in future studies.

Minimal negative effects, potential benefits of winter watering

Capturing stormwater runoff and potentially banking it in groundwater through winter irrigation in almond orchards might be a feasible method to reduce groundwater overdraft in California. In our study, over 90% of the winter-applied water percolated past the root zone (2-foot depth) in the sandy soil at Delhi and 80% percolated past the root zone in the fine sandy loam at Modesto (table 5). Our data show that this watering had minimal effects on yield, root production and light interception in both almond orchards. However, as we added extra water for recharge purposes to only one block per treatment at each site, we cannot separate the effects of differences across blocks from the effects of the recharge treatments, and thus we cannot firmly conclude that winter watering has no negative impacts on almond orchards. More rigorous and longer-term studies are necessary to confirm this low risk and perhaps explore potential horticultural advantages of winter irrigation in *Prunus* spp. orchards at different ages.

The opportunity to flood almond orchards during the dormant season may only be feasible during years when winter rains are above normal. More studies are needed to evaluate the impact of applying water for recharge purposes later, in the spring, when more surface water becomes available in most parts of the Central Valley. This is when the roots and shoots are actively growing (after blooming or during the fruit development stage, April–May), and trees that are actively growing are much more susceptible to the negative effects of low oxygen conditions in the soil (Kreuzwieser and Rennenberg 2014). In addition, due to orchard growing practices and fertilizer applications, this period is likely much less suitable for groundwater recharge (Duncan et al. 2019), as it carries an additional risk of leaching nitrates and other pollutants into the groundwater and there is a need to regularly move heavy equipment through the orchard.

Lastly, efficiency of groundwater recharge and its effects on the growth of almond trees are influenced by rootstock, soil type and other factors that affect water percolation. In order to prevent unintended tree loss, growers need to carefully consider these factors when adopting the strategy of groundwater recharge in almond orchards.

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We wish to thank the Almond Board of California for funding this project through grants 15-17 PREC9 and 20 PREC10. We also thank the Modesto Irrigation District, cooperating growers Nick Blom (Modesto) and Glen and Craig Arnold (Delhi), as well as help and advice from Dan Rivers, Sam Metcalf, Ken Shackel, Loreto Contador, Colin Fagan, Rebecca Scott, Elexia Koch, Seanna McLaughlin and Cristina Prieto Garcia. This research was partially supported by the California Agricultural Experiment Station with funding from the Hatch Act through the USDA National Institute of Food and Agriculture.

References

[CDFA] California Department of Food and Agriculture. 2020. California Agriculture Statistics Review 2019-2020. www.cdfa.ca.gov/Statistics/PDFs/2020_Ag_Stats_Review.pdf (accessed Sep. 6, 2021).

[CADWR] California Department of Water Resources. 2019. Data and Tools. https://water.ca.gov/Programs/Groundwater-Management/Data-and-Tools (accessed Jan. 28, 2020).

Dahlke H, Brown A, Orloff S, Putnam D. 2018. Managed winter flooding of alfalfa recharges groundwater with minimal crop damage. Calif Agr 72(1):1–11. https://doi.org/10.3733/ca.2018a0001

Duncan R, Gordon P, Holtz B, et al. 2019. Sample costs to establish an orchard and produce almonds. UC Agricultural Issues Center. UC Davis. https://coststudyfiles.ucdavis.edu/uploads/cs_public/79/86/79863d8a-8f8b-4379-91c9-0335e20a2dd2/2019almondssjvnorth.pdf (accessed Aug. 5, 2020).

Kozlowski T. 1997. Responses of woody plants to flooding and salinity. Tree Physiol 17(7):490. https://doi.org/10.1093/treephys/17.7.490

Kreuzwieser J, Rennenberg H. 2014. Molecular and physiological responses of trees to waterlogging stress. Plant Cell Environ 37:2245–59. https://doi.org/10.1111/pce.12310

Lampinen B, Tombesi S, Metcalf S, DeJong T. 2011. Spur behavior in almond trees: Relationships between previous year spur leaf area, fruit bearing and mortality. Tree Physiol 31:700–6. https://doi.org/10.1093/treephys/tpr069

O'Geen A, Saal M, Dahlke H, et al. 2015. Soil suitability index identifies potential areas for groundwater banking on agricultural lands. Calif Agr 69(2):75–84. https://doi.org/10.3733/ca.v069n02p75

Osmont K, Sibout R, Hardtke C. 2007. Hidden branches: Developments in root system architecture. Annu Rev Plant Biol 58(1):93–113. https://doi.org/10.1146/annurev.arplant.58.032806.104006

Tixier A, Gambetta G, Godfrey J, et al. 2019. Non-structural carbohydrates in dormant woody perennials; the tale of winter survival and spring arrival. Front For Glob Change 2:18. https://doi.org/10.3389/ffgc.2019.00018

Volder A, Smart D, Bloom A, et al. 2004. Rapid decline in nitrate uptake and respiration with age in fine lateral roots of grape: Implications for root efficiency and competitive effectiveness. New Phytol 165(2):493–502. https://doi.org/10.1111/j.1469-8137.2004.01222.x

Zarate-Valdez J, Metcalf S, Stewart W, et al. 2015. Estimating light interception in tree crops with digital images of canopy shadow. Precis Agric 16:425–40. https://doi.org/10.1007/s11119-015-9387-8