A case study of evapotranspiration at five almond orchards on a spectrum of conventional to regenerative management

A new case study demonstrates that regenerative management in almonds leads to improvements in soil moisture retention and does not result in increased evapotranspiration.

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Abstract

In an increasingly unstable climate, it is critical to optimize water needed for crop irrigation to secure food production and livelihoods while reducing environmental impacts. Here, we focus on water use for almonds — a crop that occupies roughly 20% of the irrigated agricultural land in California and has long been the focus of scrutiny. Regenerative agriculture, a term used to describe system designs that increase soil health, biodiversity, resilience to climate, and profitability while reducing greenhouse gas emissions, water use, and pollution, offers a potential way forward. We used eddy covariance, micrometeorological, and soil moisture measurements from 2022 and 2023 to quantify the evapotranspiration of California almond orchards under different soil and plant management practices and produce comprehensive estimates of the water footprint of different management systems. In five almond orchards, we find that there is little difference between evapotranspiration at regenerative and conventional sites in winter months, and that regenerative sites have similar or slightly lower evapotranspiration during the growing season. Orchards with cover crops had higher infiltration rates of winter precipitation than those without; however, soil moisture did not differ between management types. This case study demonstrates that regenerative management in almond orchards leads to improvements in soil moisture retention without guaranteeing increased evapotranspiration.

Water is an increasingly important resource globally due to climate change and increases in agricultural demand (Foley et al. 2011). In California, water is critical to maintaining irrigated agriculture as drought continues to intensify (Diffenbaugh et al. 2015; Levy et al. 2021). Optimizing management practices to increase water use efficiency and measuring and mitigating evapotranspiration in almond orchards is important for local climate adaptation and landscape-scale water conservation.

Despite water being a crucial piece of California's agricultural puzzle, little is understood about how regenerative agriculture impacts its use. Winter precipitation in particular is increasingly volatile as climate instability increases, which may make hydroclimatic extremes a normal occurrence, impacting infrastructure, environmental justice, and water access in the Central Valley (Swain et al. 2018). As such, it will be vital for Central Valley farmers to adapt their water use to drier conditions with occasional wet years and flooding.

The orchard at study site GUS2 (4). The authors found no evidence of regenerative management increasing daily evapotranspiration during the almond growing season. *Photo*: Margot Flynn.

Regenerative agricultural systems implement several core ecological principles, including reduction or elimination of synthetic agrichemicals and tillage, maintaining soil coverage and living roots, maximizing plant diversity and productivity, and integrating livestock and crops (Fenster, LaCanne, et al. 2021; Fenster, Oikawa, et al. 2021). A multitude of ecological benefits not fully measured in this study accompany regenerative management strategies such as pest suppression, increased soil and water quality, support for soil microbial communities, and nutrient cycling efficiency (Brussaard et al. 2007; Fenster, LaCanne, et al. 2021; Snapp et al. 2015; Vendig et al. 2023). Additionally, livestock integration provides growers with diversified income and can improve revenue per acre in almond orchards (Fenster, LaCanne, et al. 2021).

Regenerative management in almond orchards can increase orchard ecological and financial resilience (Fenster, Oikawa, et al. 2021); however, previous studies show mixed results for cover crop impacts on evapotranspiration and barriers to adoption remain (Bodner et al. 2007; DeVincentis et al. 2022; Mitchell et al. 2015). The goal of this exploratory case study is to examine and quantify water consumption via evapotranspiration in Central Valley almond orchards with different management practices (regenerative and conventional) using the eddy covariance method (a technique that measures turbulent gas fluxes between an ecosystem and the atmosphere) and soil moisture monitoring. Our findings illustrate a need for understanding the water use of regenerative agricultural practices to help growers and policy makers decide if they should prioritize these ecological principles and management tactics in California's irrigated landscapes.

Measuring the energy budget

In agriculture, evapotranspiration is a process by which water applied to a field cycles through the soils and plants and is released to the atmosphere as water vapor. As such, evapotranspiration is synonymous with consumptive water use, or water losses from the hydrologic basin that cannot be regained immediately. Additional evaporation from sources like soil depressions or leaf surface droplets may also reenter the atmosphere as vapor without cycling through soil and plants. We analyzed evapotranspiration at the field-level scale (20–70 acres) over a continuous 17-month period using eddy covariance measurements in California almond orchards under a spectrum of management regimes from bare soil (most conventional) to cover cropped and grazed (most regenerative) from May 2022 through September 2023, critically dry and wet years, respectively.

Experimental design

We chose five sites along a gradient of regenerative to conventional practices in California's Central Valley (fig. 1; table A-1 in the online appendix). Sites were located in a mix of Mediterranean/hot summer and semiarid/steppe climates according to the Köppen System (Critchfield 1975). From 2000 to 2021, average annual rainfall in our study areas was 243.8 millimeters (mm) per year (California Department of Water Resources n.d.). During the first winter of this study, which followed a critically dry water year, our sites had an average of 444 mm of rain — 181% greater than the average annual rainfall. Table A-1 contains site locations and characteristics as well as regenerative scores based on the 2021 growing season determined using physical variables in the scoring criteria from Fenster, LaCanne, et al. (2021). Chemical additions like fertilizer, fungicides, herbicides, or insecticides are not included in scoring because they were not relevant to the scope of this study.

We henceforth refer to sites and their regenerative scoring together to allow for easier consideration of management practices (site ID (score), e.g., MOD (1)). We assigned a "1" to regenerative practices of cover cropping, livestock grazing, no-till, and inclusion of organic amendments (table A-2). There are four categories to be scored, so scores closer to four represent more regenerative practices adopted. Sites GUS1 (2) and MOD (1) experience occasional resident vegetation growth in the winter. These vegetation mixes have minimal biomass, and are not cultivated, so they are not counted as cover crop in scoring. Estimates of these resident vegetation mixes are listed in table A-1.

Site comparisons

While all trees were mature, tree health varied. Despite being similar in age to other orchards, MER (4)

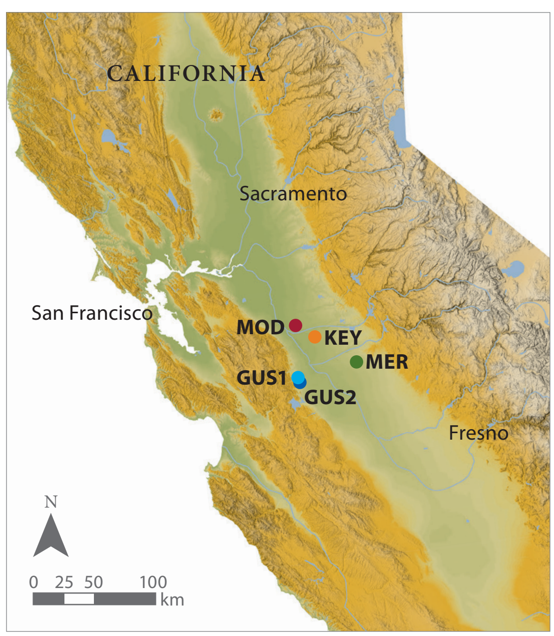

FIG. 1. Site map of almond orchard locations in the Central Valley, California. *Sources:* Esri, USGS, NOAA.

had smaller trees. As the orchard history prior to current ownership is unknown, we cannot determine the cause of stunted growth. Allen et al. (1998) reported that non-standard vegetative conditions such as lower density, height, leaf area, fertility, or vitality that we see at MER (4) may contribute to lower transpiration. In contrast, the smaller canopies shade soil less, which could lead to higher evaporation in areas with bare soil or higher transpiration in areas with cover crops. In this case, the cover crop was highly developed due to the limited competition with tree canopies.

It should also be noted that GUS2 (4) trees are reported to have some root disease, though these trees do not appear to have sub-standard aboveground characteristics and therefore effects on evapotranspiration are less clear. We include a comparison of actual daily evapotranspiration (ET_{as}) and Normalized Difference Vegetation Index (NDVI) data from OpenET to provide additional context for vegetative health. Further site details are available in table A-1. Because of these site discrepancies, our cross-site analysis of evapotranspiration is interpreted with caution and results only represent patterns found in this case study.

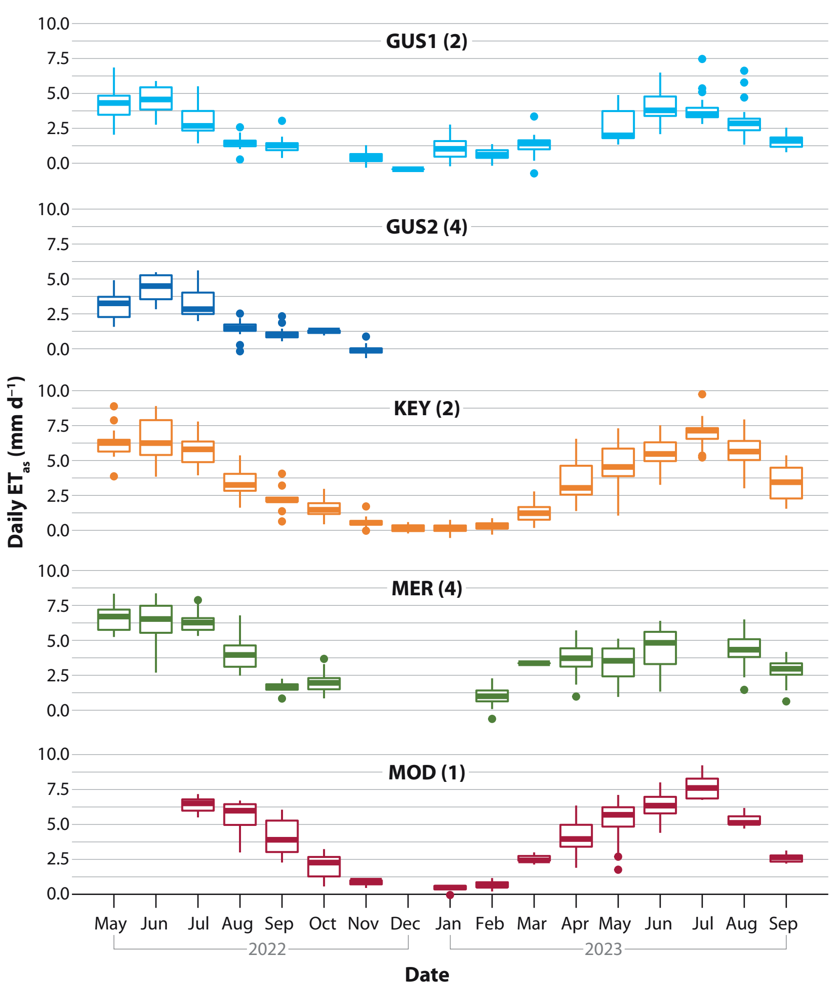

FIG. 2. Monthly box plots for daily ET_{as} in Central Valley almonds. Sites are scored from 0 (least regenerative) to 4 (most regenerative) (i.e., site ID (score)).

Data collection

We computed evapotranspiration from May 2022 through September 2023 using the residual of the energy balance method (REB), which is based on theoretical fundamental concept of conservation of energy. Within this approach, we measured three energy budget components (net radiation, soil heat flux, and sensible heat flux) and found the residual energy value (latent heat flux), an energy equivalent of evapotranspiration that we then converted to a value of actual evapotranspiration (ET_a) in volume of water per unit area (mm). In this study, daily and seasonal values were the most relevant; therefore, we report a simplified calculation of ET_{as}. This method assumes that ground heat flux averages to 0 on a daily basis and thus precludes needing soil heat flux measurements (Paw U et al. 2019). The uncertainty for this assumption is estimated to be 10 W m^{-2} or 0.3 mm day^{-1}, based on assessments of daily cumulative soil heat flux (Agam et al. 2019; Purdy et al. 2016), an error similar to eddy covariance uncertainty for half hourly data (Paw U et al. 2019).

Sonic anemometers, net radiometers, soil heat flux plates, and thermocouples were used to measure each REB component, with sensible heat measured through eddy covariance, and surface renewal as a back-up method when needed at MOD (1) from May 2022 through November 2022. In addition to continuous high frequency turbulence and REB measurements, we also took hourly, 1 meter, soil moisture profile measurements at nine depths with SoilVUE10 sensors (Campbell Scientific, Logan, Utah) located in the tree row and in the middle of the alleys on either side of the tower. Soil cores collected at the study sites were analyzed for soil texture (fig. A-1 in online appendix). We were unable to collect cores from GUS1 (2), so USDA Web Soil Survey provided soil texture data (USDA 2024). Additionally, due to a lack of sensor availability, GUS2 (4) data only span the start of the study period through November 2022. Further details about site set up, sensor models, and errors are provided in the online technical appendix in fig. A-2 and table A-3.

Data processing and analysis

We used one and a half years of data to evaluate effects of regenerative management on evapotranspiration and soil moisture. We faced typical challenges of in situ studies, including working around farm operations, sensor damage or interference from animals, machinery, and severe weather. However, the selection and quality assurance process for our data maintained the integrity of our analysis. Data availability is visualized in fig. 2 and reported in table A-6. Data were collected using Campbell Scientific CR3000 data loggers supplemented with compact flash cards for high frequency data storage. Data were converted using Loggernet software (v4.7, Campbell Scientific) and processed with EddyPro (v7.0.7, LI-COR Biosciences, Lincoln, Neb.). Processing and quality assurance details can be found in the technical appendix (table A-4 through table A-7).

We analyzed volumetric water content (VWC) data from SoilVUE10 soil profilers from locations in the middle of tree alleys at all sites. Drip irrigation at MOD (1) reached this area and all other sites had microsprinkler irrigation systems that distributed water across both alleys and rows; as such, all sensor alley positions can be assumed to be representative of whole field irrigation.

We examined data and calculated descriptive statistics for site variables at all sites using R software (R Core Team 2021). For our analysis, we used daily sums of simplified evapotranspiration values (ET_{as}) that were gapfilled on an hourly basis where wind or rain affected initial hourly measurements to allow for meaningful comparisons with fewer data gaps. Methods for gapfilling are in the online technical appendix in the section "Wind and rain flagging." Means and statistical significance tests in tables 1–4 were calculated from dates where all sites had ETas reported to ensure robust comparisons.

We visualized ET_{as} trends for each season using the ggplot2 package in R (Wickham 2016). We also used the stats package to conduct ANOVAs and Kruskal Wallis tests based on mean daily ET_{as} values from typical growing (April–September) and dormant (October–March) seasons in the region. Because of data availability limitations, the GUS2 (4) site was only included in the ANOVA for the 2022 growing season. Visualizations and statistical results were analyzed alongside site regenerative scores to identify trends. Statistical significance for the test results was designated at *P*-values < 0.05.

Evapotranspiration

Daily ET_{as} data from this exploratory case study is visualized in fig. 2. Descriptive statistics for all sites are provided for each month and year (table A-7). GUS1 (2) and GUS2 (4) showed notably lower ET_{as} patterns from the other three sites. Location alone can be a strong determinant of differences in ET_{as} so to check for local effects, we compared our data to local reference ET data. We did not see consistently lower reference ET at GUS1 (2) and GUS2 (4), which indicates that local climate did not drive the differences between these and other sites in this study.

In this case study, we see no evidence of regenerative management increasing daily evapotranspiration during the almond growing season (tables 1–4; fig. 3). During August of the growing season in 2022, sites MER (4) and MOD (1) were not significantly different, despite having regenerative scores on opposites ends of the spectrum and MER (4) being the only site with cover crops present in August. Late season cover crops at MER (4) may also explain some of the difference

TABLE 1. Mean daily ET_{as} for the available dates by season

Site	Growing season '22 Mean daily ET (mm) (*n* = 12)	Dormant season '22–'23 Mean daily ET (mm) (*n* = 16)	Growing season '23 Mean daily ET (mm) (*n* = 51)
KEY (2)	3.19	0.31	4.85
GUS1 (2)	1.60	0.61	3.29
GUS2 (4)	1.60	NA	NA
MER (4)	4.24	1.17	4.02
MOD (1)	5.42	0.64	5.22

Means and statistical significance were calculated from dates where all sites reported daily ET_{as}. These Central Valley almond sites are scored and labeled from 0 (least regenerative) to 4 (most regenerative) (i.e., site ID (score)).

TABLE 2. Kruskal-Wallis results for ET_{as} during the 2022 growing season*

Comparison	Z score	Adj *P*-value
MOD (1) – KEY (2)	2.54	0.1120
MOD (1) – GUS1 (2)	5.33	**0.0000**
KEY (2) – GUS1 (2)	2.79	0.0521
MOD (1) – GUS2 (4)	5.26	**0.0000**
KEY (2) – GUS2 (4)	2.72	0.0646
GUS1 (2) – GUS2 (4)	−0.07	1.0000
MOD (1) – MER (4)	1.19	1.0000
KEY (2) – MER (4)	−1.34	1.0000
GUS1 (2) – MER (4)	−4.14	**0.0004**
GUS2 (4) – MER (4)	−4.07	**0.0005**

* Data from the 2022 growing season and 2022–2023 dormant season were heavy-tailed, requiring non-parametric testing.
Means and statistical significance were calculated from dates where all sites reported daily ET_{as}. These Central Valley almond sites are scored and labeled from 0 (least regenerative) to 4 (most regenerative) (i.e., site ID (score)).
Bolded *P*-values are considered significant at < 0.05.

TABLE 3. Kruskal-Wallis results for ET_{as} during the 2022–2023 dormant season*

Comparison	Z score	Adj *P*-value
MOD (1) – KEY (2)	2.13	0.2006
MOD (1) – GUS1 (2)	0.09	1.0000
KEY (2) – GUS1 (2)	−2.04	0.2473
MOD (1) – MER (4)	−2.78	**0.0324**
KEY (2) – MER (4)	−4.91	**0.0000**
GUS1 (2) – MER (4)	−2.87	**0.0248**

* Data from the 2022 growing season and 2022–2023 dormant season were heavy-tailed, requiring non-parametric testing.
Means and statistical significance were calculated from dates where all sites reported daily ET_{as}. These Central Valley almond sites are scored and labeled from 0 (least regenerative) to 4 (most regenerative) (i.e., site ID (score)).
Bolded *P*-values are considered significant at < 0.05.

TABLE 4. ANOVA results for ET_{as} during the 2023 growing season

Comparison	Diff in means	95% CI	Adj *P*-value
KEY (2) – MOD (1)	−0.37	[−1.09, 0.34]	0.5264
GUS1 (2) – MOD (1)	−1.94	[−2.65, −1.22]	**0.0000**
MER (4) – MOD (1)	−1.20	[−1.91, −0.49]	**0.0001**
GUS1 (2) – KEY (2)	−1.56	[−2.28, −0.85]	**0.0000**
MER (4) – KEY (2)	−0.83	[−1.54, −0.11]	**0.0158**
MER (4) – GUS1 (2)	0.74	[0.02, 1.45]	**0.0402**

Means and statistical significance were calculated from dates where all sites reported daily ET_{as}. These Central Valley almond sites are scored and labeled from 0 (least regenerative) to 4 (most regenerative) (i.e., site ID (score)).
Bolded *P*-values are considered significant at < 0.05.

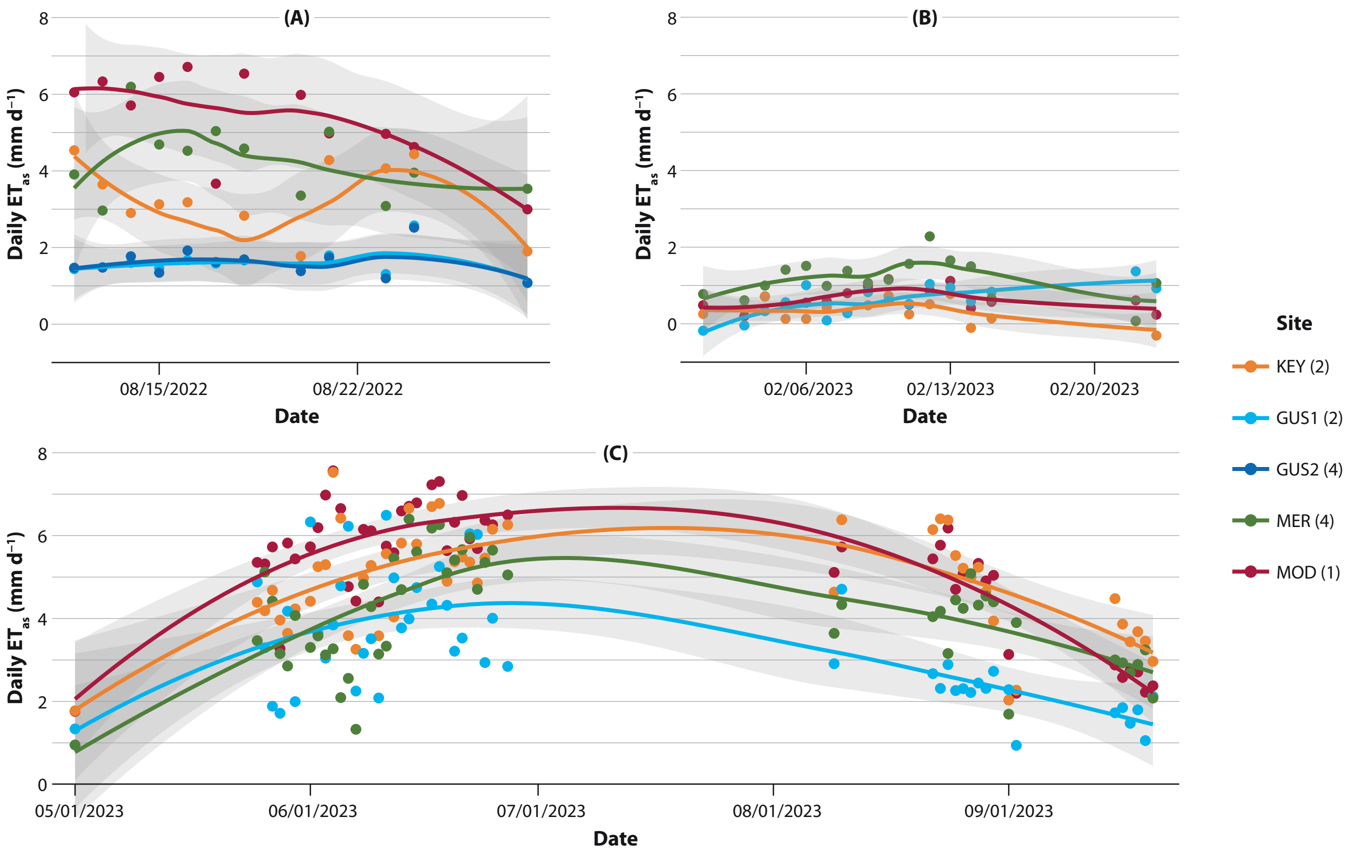

FIG. 3. (A) Daily ET_{as} data for the 2022 growing season ($n = 12$), (B) daily ET_{as} data for the 2022–2023 dormant season ($n = 16$), (C) daily ET_{as} data for the 2023 growing season ($n = 51$). Statistical comparisons are only conducted for daily values where all sites reported data. Central Valley almond orchard sites are scored and labeled from 0 (least regenerative) to 4 (most regenerative) (i.e., site ID (score)).

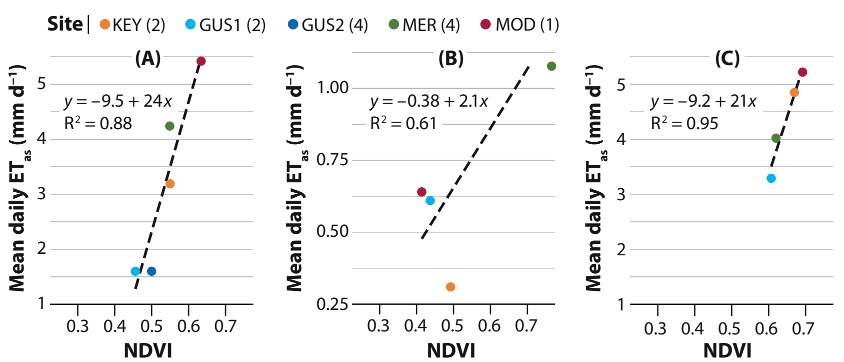

FIG. 4. Normalized Difference Vegetation Index (NDVI) compared to mean daily ET_{as} with linear regressions, equations, and R^2 for Central Valley almond orchards during (A) August 2022, (B) February 2023, and (C) May 2023–September 2023. Monthly NDVI data were sourced from the Open ET system. Sites are scored and labeled from 0 (least regenerative) to 4 (most regenerative) (i.e., site ID (score)).

between MER (4) and GUS2 (4). While daily ET_{as} at MOD (1) was consistently highest in both 2022 and 2023, other site results were mixed (fig. 3A and 3C). Across these two growing seasons, our analysis reveals no consistent patterns connecting regenerative score and ET_{as}.

In February 2023 of the dormant season, MER (4) reported the highest mean daily ET_{as}. An examination of ET_{as} compared to NDVI for this period reveals a high vegetation index at MER (4) compared to other sites. MER (4) had highest ET_{as} and NDVI, but unlike during the growing season, the February 2023 relationship between NDVI and ET_{as} is not clearly linear ($R^2 = 0.61$) (fig. 4). Every other row of cover crop at KEY (2) was mowed at the start of February 2023, which may explain the lower NDVI when compared to MER (4). However, even with some cover crops, KEY (2) had the lowest mean daily ET_{as} during this season. While ET at MER (4) was significantly higher than all other sites during February 2023, results were mixed among GUS1 (2), MOD (1), and KEY (2), suggesting cover crops were not the only contributing factor to relatively high ET_{as} at MER (4). These results indicate that regenerative management does not necessarily lead to high evapotranspiration during wet, dormant seasons (fig. 3B).

DeVincentis et al. (2022) found that winter cover cropping in Central Valley almonds did not contribute to increased water demand, which is consistent with our dormant season results. It is worth mentioning that GUS2 (4) was gapfilled for hourly wind and rain flags using hourly ET_{as} values from GUS1 (2) due to data limitations at GUS2 (4) and therefore some similarity among sites may be due to this potential data correlation. Results show slightly lower evapotranspiration in summer months at the GUS1 (2) and GUS2 (4) sites compared to the rest of the study; however, more research is needed to determine what factors are contributing to this difference.

Despite micro-sprinklers increasing evaporative potential (Koumanov et al. 1997), we see highest mean daily ET_{as} at the most conventional site, which was the only site using drip irrigation. We suspect that ET_{as} at MOD (1) would have been higher than what is reported in this case study had they used micro-sprinklers like other sites. Any influences from irrigation type should be further researched, but in this case study, the effect of irrigation type can be assumed to be understated.

Soil moisture

Deep water infiltration was highest at regenerative sites GUS2 (4) and MER (4), but results were mixed among the remaining sites which suggests that drawing a connection between regenerative score and infiltration requires additional research (fig. 5). Aside from MER (4), which experienced significant flooding and deep infiltration, soil moisture below 25 centimeters (cm) does not appear largely different at individual sites across seasons. During the dormant season, MER (4) experienced considerable flooding due to the orchard's position in a lower elevation than neighboring land and had VWC readings up to 40.3% at their 100-cm depth position. Higher October and February evapotranspiration at MER (4) may be attributed to a larger proportion of evaporation from surface soil due to flooding rather than an increase in plant transpiration, which can be temporarily inhibited by waterlogging and subsequent anoxic conditions (Liu et al. 2020). Additional physiological measurements would be required to determine this for certain.

The MER (4) site infiltrated a high amount of precipitation during the dormant season (October–March) and maintained most of this moisture at depth well into the next growing season (fig. 5). We observe that irrigation during the growing season (April–September) generally does not reach soils around 1 meter; thus, this kind of deep infiltration during the wet season can provide important soil moisture storage that is not attainable with typical irrigation regimes. Deep infiltration encouraged by cover crop roots in wet winter months may provide water for tree roots later in the season, delaying the spring irrigation start date (Joyce et al. 2002). This observation points to potential benefits of cover cropping combined with wet winters and adequate management to minimize the amount of water required during the early growing season. Deep soil moisture storage below root zones may also end up draining into deeper layers, which can recharge long-term aquifer stores and increase drought resiliency (Haruna et al. 2022).

Author Margot Flynn repositions the net radiometer at MER (4) after routine cleaning. *Photo*: Olmo Guerrero-Medina.

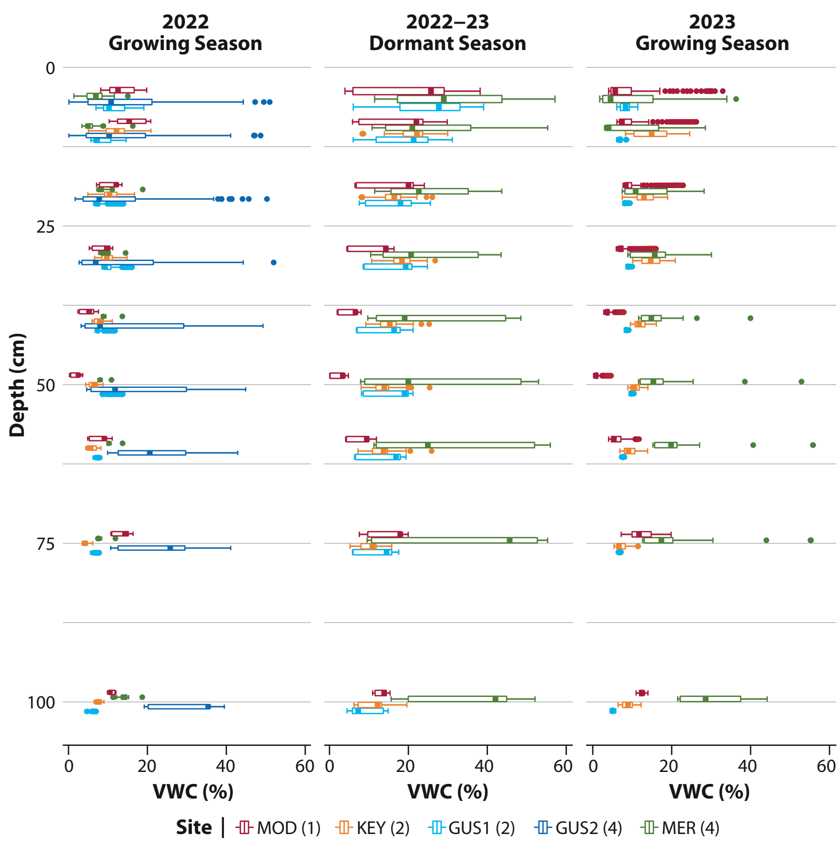

FIG. 5. Soil volumetric water content (VWC) by season for tree alley SoilVUE10 sensors in Central Valley almond orchards. Sites are scored and labeled from 0 (least regenerative) to 4 (most regenerative) (i.e., site ID (score)).

Applications and looking ahead

Our exploratory case study provides a novel perspective on regenerative agriculture through the lens of water use in California. At the five almond orchards in this study, regenerative management practices such as cover cropping and livestock integration did not lead to higher evapotranspiration in perennial crops, and likely contributed to higher soil moisture retention.

A multifunctional analysis of the benefits and potential tradeoffs of regenerative agriculture beyond our evapotranspiration and soil moisture findings is necessary to move forward with the strategic implementation of regenerative practices. Consideration of soil health, long-term farm viability, financial costs, impacts to yield, nut quality, and novel groundwater policy will increase the strength of future analyses. Research is also needed in evapotranspiration studies that include leaf area index measurements to parse out the components of evapotranspiration where cover crops make up an unknown portion of total evapotranspiration from a study area. Continued monitoring of these sites will allow for comparisons of evapotranspiration following wet and dry winters.

The socioeconomic impacts of drought and climate change in almond farming in the Central Valley are closely linked to the success of not only the industry but livelihoods in the region as well. Thus, it is of the utmost importance to continue conducting research on the possible benefits and tradeoffs of switching to more ecologically minded almond farming practices. A change such as this can decrease negative externalities while conserving biodiversity and water, improving air quality, and increasing resiliency to precipitation volatility to maintain California's agricultural industry in an uncertain hydrologic future. CA

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