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Developing tools and information on crop water use and effective irrigation management for more profitable and sustainable avocado production

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Abstract

In California, avocados are primarily grown in southern and central parts of the state along the coast. These regions face uncertain water supplies, mandatory reductions of water use, and the rising cost of water. While efficient use of irrigation water is one of the highest conservation priorities, there is currently a lack of accurate information on crop water use and optimal irrigation strategies hindering the achievement of resource-efficient and profitable avocado production. This study aimed at acquiring relevant information on evapotranspiration and developing more precise and representative crop coefficient values for 'Hass' avocados under different environments and cropping systems in California. Extensive data collection was conducted at five avocado sites located in major avocado production regions over a three-year period using cutting-edge ground- and remote-sensing technologies. A combination of eddy covariance and surface renewal techniques were utilized to measure actual crop evapotranspiration (ETc act), which were used to develop actual crop coefficient (Kc act) curves that were affected by various climate, crop canopy, slope, elevation, salinity, and soil management features. The results clearly illustrated that the water consumption of avocado orchards is affected by site-specific conditions. Across the experimental sites and study seasons, the seasonal ETc act totals fell within the range of 713 mm to 1,028 mm. Considerable variability was found in crop coefficient values of avocado sites, both spatially and temporally. The findings demonstrated greater Kc act values during the flower bud development, and flowering through fruit set growth phases than the fruit development phase, ranging from an average of 0.7 to 0.85 over the season at the site with the highest values. Daily mean ETc act in spring and summer was 3.4- and 3.8-mm d^{-1}, respectively, whilst winter and fall had a similar daily mean ETc act (2.0 mm d^{-1}) at this site. In contrast, the range of Kc act was 0.55-0.73 at the avocado site with the lowest values where the coastal climate reduced ETc act relative to standardized reference ETo. The information developed by this study enables farmers to determine the water needs of avocado orchards in a more reliable, usable, and affordable format, and it assists local water districts with their water delivery and conservation programs.

1. Introduction and Background

In California, avocado is primarily grown in southern and central parts of the state along the coast. These regions have semi-arid Mediterranean climates with winter-dominant rainfall, and currently face uncertain water supplies, mandatory reductions of water use, and rising cost of water. Consequently, efficient use of irrigation water is one of the highest conservation priorities. Moreover, due to increasing salinity in water sources and the fact that avocado trees are sensitive to salinity, effective irrigation is more critical to ensure optimal yield and high-quality avocado fruits. Many avocado farmers have developed irrigation practices that enable good profitability, however, the continuing increase in water costs and water restrictions due to

1

drought and climate change have placed pressure on the industry to further enhance water use efficiency. Accurate information on crop water use along with irrigation best management practices are the immediate needs of the avocado industry under the current fluctuations in water availability, reliability, and quality to sustain the profitability and sustainability of production in California.

Most studies on avocado crop water consumption have focused on determining the level of water application necessary to obtain satisfactory fruit set, size and yield rather than directly determining the actual water use of the trees and/or crop coefficient values. There were only a few attempts to measure the actual water use of avocados in California and worldwide and, therefore, data on water use by avocado orchards is limited.

The main purpose of this study was to acquire more precise crop water use and crop coefficient information for California Hass avocado production systems. It aimed to better understand the impacts of environmental and plant factors on crop water use and to conduct an assessment on potential seasonal variations of crop coefficient values. The novelty of the study is using the Residual Energy Balance (REB) measurements with a combination of eddy covariance (ECov) and surface renewal (SR) techniques to determine the sensible heat flux density. To our knowledge, this method has not been used to measure the ET of Hass avocados at large scale and on a wide range of terrain slopes. While there is a lack of information on the water use of Hass avocado orchards, this study may provide data sets and information that can serve as a reference for further studies and applications to avocado production in other production systems.

2. Field measurements

This research was conducted at 12 "Hass" avocado sites in southern California, spanning San Diego, Riverside, Orange, and Ventura Counties over a three year period. The experimental sites encompass a diverse range of climates, planting densities, spatial variations influenced by slope and elevation, canopy characteristics and management practices, predominant soil types and conditions, water sources, and irrigation strategies typical of California's avocado production systems. Additionally, the sites reflect the distinct growing conditions found in both the inland valleys and coastal regions of California.

The eddy covariance and surface renewal techniques were used to measure the sensible heat flux density (H) between the crop and the atmosphere that in turn was used to calculate the latent heat flux density (LE) using measurements of net radiation (Rn) and ground heat flux density (G). The daily LE was derived as the sum of the 48 half-hourly LE calculations from midnight to midnight. Daily LE ($MJ\ m^{-2}\ d^{-1}$) was converted to daily actual ETc act ($mm\ d^{-1}$) as ETact = LE/2.45. Note that 2.45 $MJ\ kg^{-1}$ is the approximate energy needed to vaporize 1.0 mm depth of water from a 1.0 m^2 surface area. While ETc act from the eddy covariance methos is used in the analysis, SR data was used when ECov data was missing. A more detailed description of the methodology and instrumentation is available in a recent journal article published on this study (Montazar et al., 2025).

Using the daily ETc act determined in each experimental site and the daily reference ET (ETo) retrieved from the spatial CIMIS (California Irrigation Management Information System) data (CIMIS website) for the coordinates of the corresponding ET tower, the daily actual crop coefficient (Kc act =Ks×Kc) was calculated for each site, where Kc act = ETc act /ETo and Ks is a daily stress coefficient, represents water and salt stress, management, and environmental multipliers. Spatial CIMIS combines remotely sensed satellite data with traditional CIMIS stations data to produce site specific ETo on a 2-km grid, which provides a better estimate of ETo for the individual sites.

A MicaSense Altum camera was mounted on a DJI Matrice 200 uncrewed aerial vehicle (UAV) to collect multispectral reflectance and thermal imagery across the avocado sites. The UAV flew parallel to the ground on each side to avoid image resolution variability. The spectral imagery was radiometrically calibrated using the MicaSense reference panel and Altum's downwelling light sensor. Then, they were processed in Pix4D Mapper to generate reflectance/thermal mosaics, point clouds (photogrammetry), and digital surface models (DSM). Historical Google Earth imagery was employed to determine tree positions and row and column spacings. These parameters facilitated accurate georeferencing of the radiometrically corrected images. The DSM was used to create a canopy height model (CHM) to calculate each tree's canopy height and area. A seam-carving method was then applied to CHM to segment trees and create a polygon for each tree canopy (Fig. 2). Canopy height and area, as well as other spectral and thermal features, were extracted for each tree using these polygons. The canopy coverage percentage of each tree was calculated using the canopy area obtained for the tree and the tree spacings in each site. The UAV imageries were taken three-four months after pruning trees in each site.

Fig. 1. A demonstration of flux tower monitoring station and some of the instrumentation set up. It demonstrates a ground view of a flux tower (a), an aerial view of a tower from a distance (b), a net radiometer and two 76.2 µm diameter chromel-constantan thermocouples above the canopy (c), a sonic anemometer and a EE181 temperature-RH sensor above the canopy (d), and a set of various soil moisture sensors and dataloggers including Watermark and IRROcloud IC-10 sensor monitor, TDR-310W Sensor and mini SDI-12 datalogger, Teros 54 and CropX V4 soil moisture probes (e-g).

Soil properties were surveyed and characterized within a different footprint area around the flux monitoring towers in each site based on geography of borders and roads. Surveys of the soil apparent electrical conductivity (ECa) were taken along the micro-sprinkler lines of each row, ignoring the two trees at either end of the row where a road was present. Measurements of ECa were conducted using a mobile dual-dipole electromagnetic induction conductivity meter,

Geonics EM-38MK2. The six sampling spots were considered as minimum locations needed to survey salinity at the towers' footprints. At each site, soil cores at four distinct depth ranges (30 cm intervals down to 120 cm at each sampling point) were taken from the six sampling locations. ECe (soil electrical conductivity) of soil samples were determined through laboratory analysis.

A combination of Watermark Granular Matrix Sensors and CropX soil moisture sensors V4 were used to monitor soil matric potential at the depths of 0.15, 0.30, 0.45, 0.60, 0.90 m and volumetric water content (VWC) at the depths of 0.20, 0.40, 0.66 m, respectively. The soil moisture sensors were set up between the tree trunk and nearest micro-sprinkler, within 30-40 cm away from the tree trunk but not close to the micro-sprinkler. The Watermark sensors data was recorded by IRROcloud IC-10 sensor monitor and the data of CropX V4 sensors were accessed through the CropX cloud on a 30-minute basis, respectively.

Fig. 2. Plant identification by seam-carving method (a), and a demonstration of the trees around the flux tower (yellow polygons) (b) at the AV5 experimental site.

3. Results

The trends in crop coefficient values were consistent across the various sites; therefore, results from five representative avocado sites (AV1–AV5) (Table 1) are presented in this report.

3.1. Canopy coverage and tree height

A high variability in canopy coverage (CC) among individual trees was observed at all sites, while the mean CC values differed across the experimental locations (Table 2). The mean canopy coverage ranged from 44.2% (standard deviation=SD=9.7%) at site AV3 to 88.7% (SD=10.2%) at site AV1. The mean canopy coverage around the tower was slightly higher in some of the sites. For instance, the value was 76.7% and 90.2% at sites AV4 and AV1, respectively. The canopy characteristics around the monitoring tower have the most influence on the measured ETc act. While the CC % is likely the most applicable and understandable canopy-related indicator for farmers, the mean canopy area of avocado trees is another canopy feature measure that may provide a better understanding of the impact of avocado tree canopy on crop water use. The mean tree canopy area varied from 11.2 m^2 (SD=3.3 m^2) at site AV3 to 31.7 m^2 (SD=4.8 m^2) at site AV1 (Table 2).

The results illustrated that site AV1 had the tallest trees across the avocado sites. The mean tree height was estimated to be 7.1 m (SD =1.65 m) for the entire site and 7.3 m (SD =0.80 m) around the tower at site AV1. The mean tree trunk diameter at site AV1 was 28.2 cm (SD=2.2 cm) around the flux tower. The trees were shortest at sites AV3 and AV4, with a mean tree height of 3.3 m (SD =0.53 m) at site AV3 and 3.8 m at site AV4.

Table 1. General information about experimental avocado sites.

Experimental site	Age of trees (in 2022)	Tree spacings (m × m)	Micro sprinkler flow rate (L h^{-1})	True elevation of the monitoring station (AMSL)	Row aspect & slope (%)	Water source	Growing region
AV1	11-year	5.8 × 5.8	95	231	South, 44%	District water	San Pasqual Valley (region 1)
AV2	8-year	4.6 × 5.5	36	454	Southeast, 20%	District water	Via Vaquero Temecula (region 2)
AV3	5-year	4.6 × 5.8	28	137	Southwest, 12%	Reclaimed water	Orchard Hills Irvine (region 3)
AV4	5-year	3.7 × 4.3	30	50	Southwest, 3%	District water and groundwater	West Saticoy (region 4)
AV5	18-year	5.5 × 5.5	40	144	South, 4%	Groundwater	Santa Paula (region 5)

Table 2. Mean (± standard deviation) tree height, canopy area, and canopy coverage (CC) percentage at the avocado sites. The living trees in each of these avocado sites were considered in the calculations. The canopy area, CC %, and tree height were reported using the measurements conducted in September 2022 at the AV1-AV3 sites and in May 2024 at the AV4-AV5 sites.

Site	AV1	AV2	AV3	AV4	AV5
Total number of surveyed trees	712	895	955	1,006	776
Height (m)	7.1 ± 1.65	4.3 ± 0.92	3.3 ± 0.53	3.8 ± 0.48	6.8 ± 1.17
Canopy area (m^2)	31.7 ± 4.8	19.4 ± 7.6	11.2 ± 3.3	12.2 ± 2.9	23.5 ± 5.1
Canopy coverage (%)	88.7 ± 10.2	72.7 ± 25.1	44.2 ± 9.7	75.9 ± 15.1	79.4 ± 19.5

3.2. Salinity effects

Salinity within the soil profile varies over the season and between the seasons affected by rainfall, irrigation management, leaching practices, irrigation water quality, and soil types and conditions. For instance, a comparison of the soil profile ECe distribution at site AV3 (Fig. 3) illustrated that the salinity noticeably declined in April 2023 after the wet winter 2023 in comparison with September 2022 when a salt-affected condition was observed at this site. A very similar result has been observed on the other sites as well. Given that the majority of the fine feeder roots in avocados that take up water and nutrients are restricted to a depth of 10 cm, this upper zone is the most critical for salinity management. If the soil is not properly leached, the first impact of salt accumulation in the upper soil will be lack of water uptake for the trees due to the osmotic effects that prevent the entry of water into the plant roots.
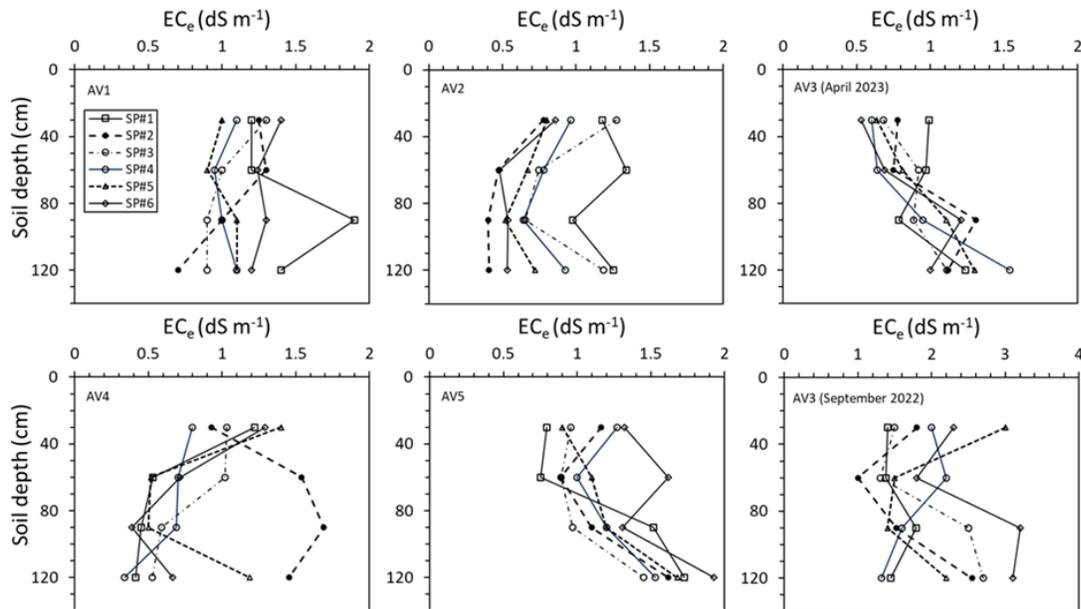

Fig. 3. Soil profile ECe observed values in different sampling points at the experimental avocado sites. The values were reported for the survey conducted in April-May 2023. For site AV3, the data was also reported from an additional survey conducted in September 2022.

Another evidence of soil salinity variabilities over the season/s is the bulk electrical conductivity values measured by CropX sensor at site AV1 (Fig. 4). The data indicated that the bulk electrically declined from 388 μS/cm on June 23, 2022, to 95 μS/cm on February 8, 2023, at this site. The avocado sites occasionally could experience salt accumulation more than the threshold while wet winter and appropriate leaching practices may have a significant impact on maintaining salt and chloride issues.

3.3. Soil moisture status

The half-hourly soil matric potential measured at 25 cm depth using Watermark sensors are shown in Figure 8 for sites AV2 and AV3. The data demonstrated that the soil water was maintained within the optimal range at both sites due to frequent irrigation events. A relatively late irrigation event could have occurred in mid-June 2022 at site AV2, when the soil matric potential exceeded -70 kPa (Fig. 5a). Also, scheduling a light irrigation event in mid-February 2023 at this site could have benefited the avocado trees. Even though considerable precipitation occurred in winter 2023, there was no rain event between late January through February 20,

2023, at site AV2, and consequently, the soil matric potential exceeded -100 kPa for a short period of time until new precipitation occurred in late February. The soil matric potential between the two sites is different because of differences in applied water and soil texture.
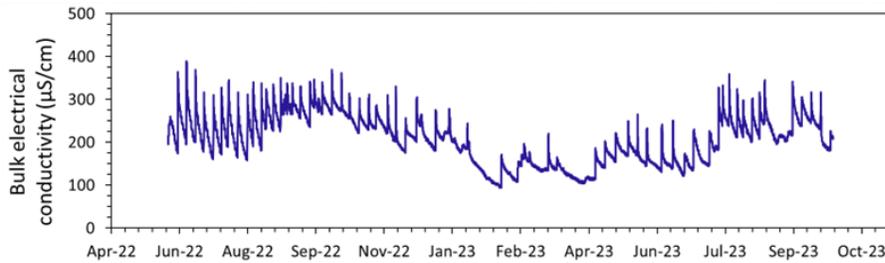

Fig. 4. Half-hourly bulk electrical conductivity data from CropX sensor at 20 cm depth at site AV1. The data is reported for a 16-month period (June 9, 2022, through October 8, 2023). A wet winter was observed in the 2023 season. The ECe value measured on two different dates of September 17, 2022, and May 4, 2023, at the same depth was 1.69 dS/m and 0.84 dS/m, respectively.
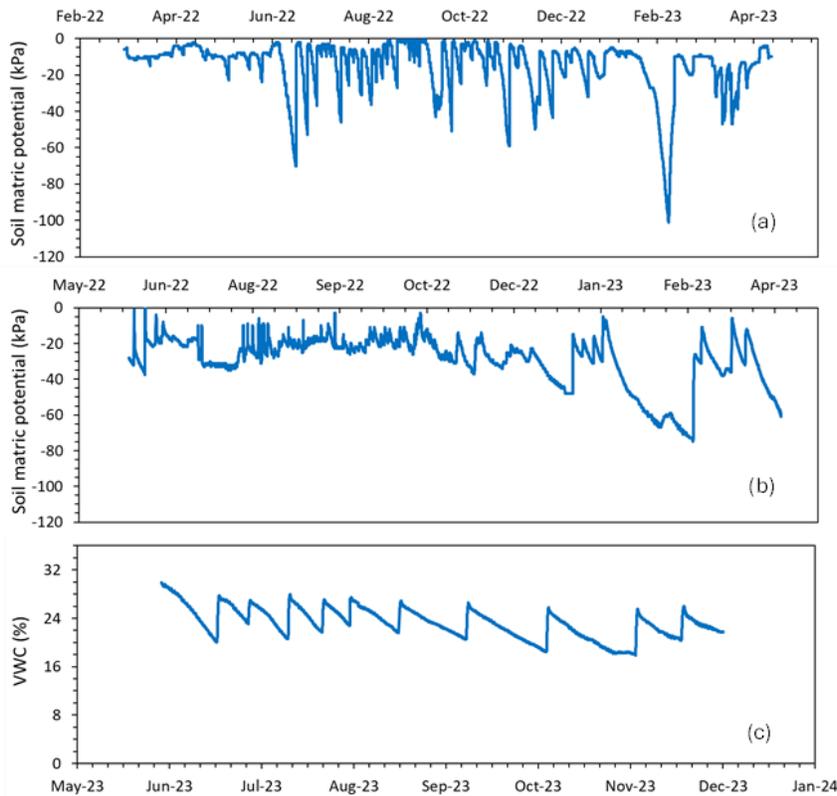

Fig. 5. Half-hourly soil matric potential (kPa) and soil volumetric water content (VWC) (%) measured using watermark sensors at 30 cm depth (a-b) and CropX soil moisture probe at 20 cm depth (c). Fig. a shows the soil matric potential (SMP) data at site AV2 (April 2022 through April 2023), Fig. b shows the matric potential data at site AV3 (June 2022 through April 2023), and Fig. c presents the VWC (%) data at site AV4 (June 2023 through December 2023). At field capacity, the soil matric potential is approximately -12 kPa at site AV2 and -20 kPa at site AV3, and the volumetric water content is approximately 28% at site AV4. The micro sprinkler flowrates per tree were 36, 28, and 30 L h^{-1} at the AV2-AV4 sites, respectively. Soil matric potential at field capacity (FC) and permanent wilting point (PWP) are nearly -13 kPa and -500 kPa at site AV2, and -18 kPa and -1,500 kPa at site AV3, respectively. Volumetric soil water content at FC and PWP at site AV4 is approximately 27 % and 11%, respectively. Water stress threshold for site AV2 to AV4 are approximately -50 kPa (SMP), -60 kPa (SMP), and 17% (VWC), respectively.

Site AV3 was likely occasionally overirrigated during the summer but again one irrigation event in mid-February 2023 could be beneficial for this avocado site as well, to maintain soil water status at a desired level in the late flower bud development phase (Fig. 5b). The soil moisture data indicates that less frequent irrigation events at site AV3 and shorter irrigation runs at site AV2 could be considered in the summer period to improve irrigation efficiency.

A good example of proper irrigation scheduling in avocado orchards is what happened in a 6-month period at site AV4 (Fig. 5c). The loamy soil texture at this site has high water holding capacity and 10 irrigation events were scheduled between mid-July and mid-December in the 2023 season. As a result of proper irrigation management at this site, the volumetric soil water content at the effective root zone was maintained at an average of 23.5% over the period. No considerable overirrigation or potential moderate water stress was observed, as soil moisture was adequately maintained throughout the study period.

Overall, a similar soil moisture status reported in Fig. 5 were observed in other sites and seasons, confirming a good soil moisture maintaining during the 2022-2024 seasons. No critical soil-water depletion, which demonstrates potential severe water stress, was observed during the study period. However, a few moderate water depletion events were observed over the study seasons.

3.4. Actual evapotranspiration and crop coefficients

The daily ETc act was determined by calculating half-hourly latent heat flux density, using the REB approach with the ECov technique, however, half-hourly LE calculated using the SR technique was used at the ETc act data for the days that there was missing data on the ECov data set. The daily spatial CIMIS ETo, ETc act from the energy flux data, and corresponding Kc act values at sites AV1 and AV3 over the study period (992 days) are shown in Fig. 6. While a similar ETc act pattern was found over the course of the measurement seasons in both sites, ETc act was generally greatest at site AV1. For instance, it varied from 0.8 mm d^{-1} to 4.7 mm d^{-1} with an average of 2.7 mm d^{-1} in the 2023 season at site AV1 (Fig. 6 and Table 3). It ranged between 0.5- and 4.1-mm d^{-1} with a mean of 2.1 mm d^{-1} in this season at site AV3. As expected from the weather data, the ETo and ETc act daily rates were lower in winter when conditions were cooler, and the days were shorter.

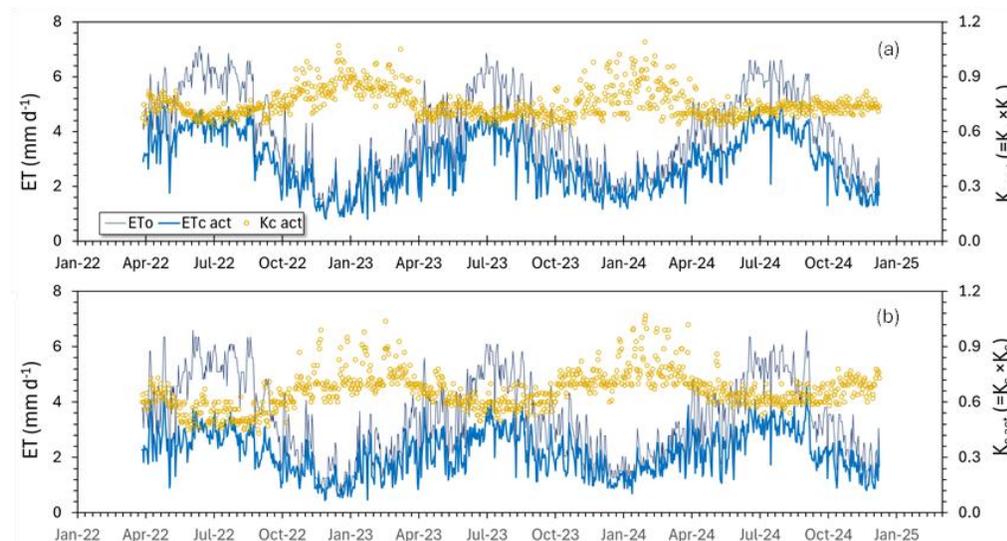Fig. 6. Daily reference evapotranspiration (ET$_o$), daily actual evapotranspiration (ET$_{c\ act}$), and daily actual crop coefficient (K$_{act}$) at the AV1 (a) and AV3 (b) sites over the measurement period (April 2022 - December 2024).

Considerable differences were found in the cumulative ETc act (CETc act) amounts determined across experimental sites and seasons. The largest CETc act difference was 291 mm between AV1 and AV4 during 2024. However, the CETc act difference between AV3 and AV4 was 52 and 61 mm in 2023 and 2024, respectively. The total water applied (irrigation + precipitation) was more than the CETc act determined across the sites and seasons (Table 3).

The trends in daily Kc act values were similar across experimental sites over the study period, with more Kc act variability during late fall and winter months when compared with spring and summer months (Fig. 6). During late-fall and winter, the weather is more unstable with more cloudy and rainy days and wet soils. More fluctuations in Kc act values are expected under such circumstances. The daily Kc act value varied from 0.61 to 1.10 with a mean of 0.75 at site AV1 over the 992-day study period. The Kc act value ranged between 0.43 and 1.06 with an average value of 0.66 at site AV3 in the same period.

3.5. Seasonal variations of avocado crop water use and crop coefficient

The observed daily ETc act and Spatial CIMIS ETo in each of the experimental sites were used to compute the mean monthly Kc act values at each site over the study seasons (Fig. 7). The results demonstrated that there is considerable spatial and temporal variability in crop coefficient values of avocado orchards. At site AV1, the monthly Kc act value varied between 0.70 (SD = 0.02) in July-August and 0.85 (SD = 0.04) in January. This avocado site had a sandy loam, non-saline soil with an average canopy coverage of 88.7% (and an average tree canopy area of 31.7 m^2) and 7.1 m tree height. The site has a 44% south facing row orientation slope, which was the maximum slope of the sites, and a density of 297 plants ha^{-1}. The south facing high slope along with the large canopy coverage are likely the most influential drivers in the environmental conditions of this avocado site, which tends to receive higher direct sunlight and light interception resulting in high crop coefficient values over the season.

In the Northern Hemisphere, midday and daily total solar radiation is mostly greater on southern slopes than on northern slopes and the slope aspect influences carbon uptake rates by altering soil moisture, temperature, and incoming light intensity. Differences in slope and aspect cause differences in air and soil temperature, moisture content, and evaporation, which creates microclimatic zonation. These differences are associated with alterations in vegetation structure and composition. Knowing the impact of slope and aspect on crop water use and crop coefficients, there should not be a significant difference affected by the aspect among the experimental sites due to similarity in row orientations (south, southwest, southeast). When the radiation is the same in the morning and afternoon on a southeast and southwest slope, the afternoon ET will be higher on the southwest slope because of the higher afternoon temperature.

The highest net radiation was observed at site AV1, and it is associated with the steep slope and canopy size at this orchard (Fig. 8). The south facing slope led to more solar radiation interception and light pruning practices are factors that led to a larger canopy and a maximum Rn=18.84 MJ m^{-2}d^{-1} on May 14, 2023. More variable daily Rn was observed in the winter and spring than in the summer and fall months. The lowest mean daily Rn values were observed during the months of December and January with 3.74 and 4.14 MJ m^{-2}d^{-1} in the 2022 and 2023, respectively.

The monthly Kc act value varied from 0.55 (SD = 0.03) in July to 0.73 (SD = 0.05) in January at site AV4, located at a low elevation (50 m AMSL) with an average of 75.9% cover canopy (and an average tree canopy area of 11.2 m^2), high density of 628 plants ha^{-1}, and 3.8 m tree height. More spatial variation was observed on the ECe values within the soil profile at this site where had a loamy soil texture and a blending water management strategy was followed over years.

Table 3. Maximum, minimum, and mean daily actual evapotranspiration ($ET_{c\ act}$), cumulative actual evapotranspiration ($CET_{c\ act}$), cumulative reference evapotranspiration (CET_o), irrigation amount, and participation at experimental sites over the 2023 and 2024 seasons.

Variable	Experimental site and season														
	AV1			AV2			AV3			AV4			AV5		
	2022	2023	2024	2022	2023	2024	2022	2023	2024	2022	2023	2024	2022	2023	2024
Maximum ET_{act} (mm d^{-1})	4.9[*]	4.7	4.9	4.9[*]	4.6	4.5	4.3[*]	4.1	4.6	-	4.0	4.0	-	4.5	4.1
Minimum ET_{act} (mm d^{-1})	0.8[*]	0.8	1.1	0.5[*]	0.5	0.9	0.5[*]	0.5	0.7	-	0.5	0.4	-	0.5	0.4
Mean ET_{act} (mm d^{-1})	3.3[*]	2.7	2.8	2.8[*]	2.3	2.4	2.4[*]	2.1	2.2	-	2.0	2.0	-	2.2	2.2
CET_{act} (mm)	846[*]	979	1,028	736[*]	847	876	612[*]	775	798	-	713	737	-	795	802
CET_o (mm)	1,160[*] (1,484)	1,332	1,396	1,127[*] (1,440)	1,270	1,325	1,024[*] (1,330)	1,159	1,192	-	1,174	1,180	-	1,246	1,268
Irrigation (mm)	1,088[*]	1,051	1,447	906[*]	773	1,102	894[*]	842	879	-	450	416	-	858	792
Precipitation (mm)	127[*]	594	354	142[*]	630	438	165[*]	695	481	-	659	421	-	802	579

[*]The amounts were reported for a 260-day period (measurements conducted) for this season (April 15 – December 31).
The numbers inside parentheses demonstrate the CET_o for a 365-day period in the 2022 season at the AV1-AV# sites (January 1 – December 31).
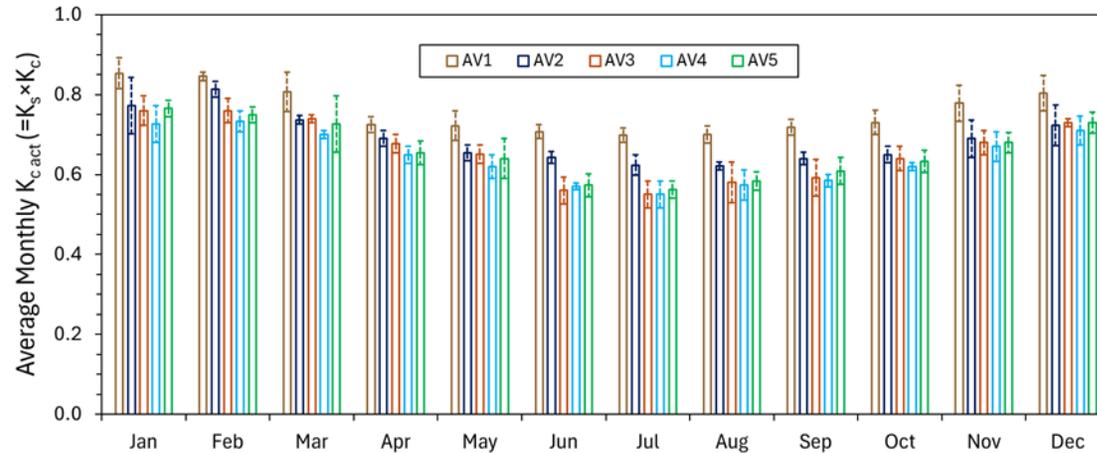

Fig. 7. Mean monthly actual crop coefficient ($K_{c\ act}$) values at the experimental avocado sites. The observed daily actual evapotranspiration ($ET_{c\ act}$) and Spatial CIMIS ET_o on each site were used to compute the monthly mean $K_{c\ act}$ values over the study period. Standard deviation (SD) of the corresponding $K_{c\ act}$ values is shown on the bars
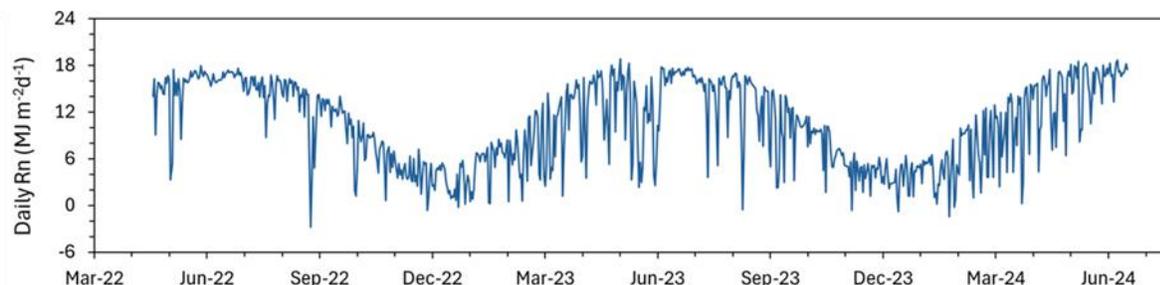
Fig. 8. Daily net radiation (Rn) at site AV1 over an 808-day period (April 16, 2022, through June 22, 2024).

A comparison was conducted calculating the percentage difference of the monthly Kc act values of sites AV1-AV3, and AV5 than the monthly Kc act values at site AV4 (with the lowest Kc act values across the study sites) (Table 4). Ste AV4 was more affected by the coastal fog influence than the others that could be a major reason for less crop water needs over the season. The maximum difference was found between the monthly Kc act values of site AV1 and site AV4, ranging from 11.5 % greater in April to 27.0 % greater in July. More differences were obtained in the June-September period, when lower Kc act values determined than in the other months of the year. A very similar trend was found at site AV2 with the lower difference values. Inversely, more differences (the values are relatively low) were obtained in the winter months at site AV3 that could be caused by the green ground cover between tree rows during the winter at this site.

Table 4. The percentage difference of the monthly $K_{c\ act}$ values of sites AV1-AV3, and AV5 than the monthly $K_{c\ act}$ values of site AV4 (with the lowest $K_{c\ act}$ values across the study sites). The monthly $K_{c\ act}$ values at site AV4 were considered as the baseline values for this comparison. The values were computed by subtracting the monthly $K_{c\ act}$ of each site from the corresponding monthly $K_{c\ act}$ of site AV4 dividing by the monthly $K_{c\ act}$ of site AV4.

Variable	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
% difference of $K_{c\ act\ (AV1)}$	17.4	15.3	15.3	11.5	16.5	24.1	27.0	22.1	22.9	17.8	16.2	13.2
% difference of $K_{c\ act\ (AV2)}$	6.1	10.9	5.3	6.2	5.5	12.7	13.4	8.4	9.4	4.8	3.0	1.9
% difference of $K_{c\ act\ (AV3)}$	4.5	3.6	5.7	4.2	5.0	-1.8	0.0	1.2	1.2	3.2	1.5	2.8
% difference of $K_{c\ act\ (AV5)}$	5.2	2.2	3.8	0.6	3.2	0.5	2.2	1.8	4.1	2.1	1.5	2.8

The results illustrated that summer has the lowest crop coefficient values, increasing gradually from late September to a maximum in mid-winter, again gradually reducing during spring to a minimum in mid-summer. To be more precise, the findings revealed greater Kc act values of avocados during flower bud development, and flowering through fruit set growth phases than the fruit development phase. Possible reasons for such a trend are:

(1) avocado leaves have a thick waxy cuticle that may reduce water loss through leaf surface and stomata. Young leaves, flowers, and young fruit do not have a fully developed cuticle and may lose more water. Researchers reported that during flowering, as some of the floral parts have stomata, the evaporative surface of the avocado tree canopy increases by up to 90%, leading to an increment of the total tree transpiration rate.

(2) avocado requires high energy in fall and winter for oil accumulation in fruit and floral development and, therefore, the trees may transpire at a higher rate compared to grass (ETo) during these months for photosynthetic activity throughout the growing season.

(3) the avocado sites are all in winter rainfall regions where weather is typically more unstable and the soils would likely experience more wetted conditions, resulting in variable and higher Kc

act values in winter. Greater Kc values in winter were reported by other researchers for citrus and olive.

Due to the large day-to-day variations in ETc act affected by fluctuating microclimate conditions, more meaningful crop water use data is obtained by calculating seasonal and/or monthly averages (Table 5). Daily average ETc act in spring and summer was 3.4- and 3.8-mm d^{-1}, respectively, whilst winter and fall had a similar daily average ETc act (2.0 mm d^{-1}) at site AV1. A similarity was found for the average daily ETc act of winter and fall seasons at the other avocado sites as well. This measure varied from 2.7 (SD= 0.2) mm d^{-1} at site AV1 to 3.8 (SD=0.2) mm d^{-1} at site AV4 over the summer months; and ranged between 1.5 (SD=0.0) and 2.0 (SD= 0.1) mm d^{-1} at the corresponding sites in the winter months. It needs to be noted that the average crop water use values are site specific, and comparisons are not entirely valid unless more definitive information on avocado sites and their similarity is known.

Table 5. Mean ET$_{c\ act}$ and standard deviation (± SD) (mm d^{-1}) in different seasons at the experimental avocado sites.

Season	Avocado experimental sites				
	AV1	AV2	AV3	AV4	AV5
Winter	2.0±0.1	1.7±0.2	1.7±0.1	1.5±0.0	1.6±0.1
Spring	3.4±0.1	2.9±0.2	2.5±0.2	2.3±0.2	2.5±0.2
Summer	3.8±0.2	3.3±0.1	2.8±0.1	2.7±0.2	2.9±0.1
Fall	2.0±0.1	1.7±0.1	1.6±0.2	1.5±0.1	1.6±0.1

4. Conclusion

While a similar seasonal ET$_{c\ act}$ pattern was found over the course of the experiment, remarkable differences were observed in the cumulative ET$_{c\ act}$ amounts determined across the study sites and seasons. The largest seasonal difference of 291 mm was observed between sites AV1 and AV4 obtained during the 2024 season where AV1 had the highest CET$_{c\ act}$. Daily mean ET$_{c\ act}$ in spring and summer was 3.4- and 3.8-mm d^{-1}, respectively, whilst winter and fall had a similar daily mean ET$_{c\ act}$ (2.0 mm d^{-1}). A mean seasonal K$_{c\ act}$ value of 0.75 was determined at an avocado site with the features of coarse sandy loam soil texture, 44% south facing slope, average elevation of 231 m AMSL, plant density of 297 tree ha^{-1}, mean canopy coverage of 88.7% and tree height of 7.1 m. In contrast, the mean seasonal crop coefficient value of 0.66 was observed for an avocado site affected by coastal climate with features of loamy soil texture, 3% southwest facing slope, average elevation of 50 m AMSL, plant density of 628 tree ha^{-1}, mean canopy coverage of 75.9% and tree height of 3.8 m. The findings illustrated that more water was applied than the total crop water consumption at these two and the other sites over the study seasons, demonstrating a need to correct water management at the farm level.

The trends in seasonal K$_{c\ act}$ values were similar for all sites over the study period, with the lowest values in summer increasing gradually from late September to a maximum in mid-Winter, and again gradually reducing during spring to a minimum in mid-summer. The new coefficient values developed by this study enable the avocado industry to utilize water more efficiently and to achieve full economic gains in a sustainable manner, especially as agricultural water becomes more expensive and less available. Several factors impact the variability of crop coefficient including irrigation management practices, salinity and/or soil differences, slope and row orientation, elevation, height of trees, and trees canopy coverage that provides a good indication of canopy size and the amount of light interception. Slope and row orientation along with canopy coverage percentage are likely the most influential drivers on avocado crop water

use and crop coefficients values. It is important to emphasis a few points on the analysis provided here when evaluating the values' applicability for other locations, including:

(1) The crop coefficient values reported here are actual crop coefficients that are calculated as: $K_{c\ act} = ET_{\mathbf{c\ act}}/ET_o$ rather than standard crop coefficients expressed as: $K_c = ET_c/ET_o$. ET_c stands for potential crop ET. This approach was applied because of a realistic expectation regarding potential water, salinity, and heat stress in avocados during crop seasons. For the periods with stem water potential above the considered threshold for water stress, The $K_{c\ act}$ can be considered as standard K_c and furthermore compared to the previously tabled values.

(2) Spatial CIMIS ET_o was used rather than the ET_o of individual CIMIS station in different regions. This approach may provide a more accurate estimate of ET_o for avocado sites under specific landscape and production systems in California avocados, however, the variability in the ET_o might be a factor causing differences in $K_{c\ act}$ values compared to what was reported.

(3) The results of this study are likely representative of avocado orchards under wet and near-normal winter conditions (the 2023 and 2024 seasons). However, because measurements were not available for the entire 2022 winter, identified as a dry winter, the crop coefficient values for winter months in dry years could be lower than those presented in this report.

Further details about this work can be found in the following reference:

Montazar, A., Faber, B., Corwin, D., Pourreza, A., Snyder, R.L. (2025). Quantifying Evapotranspiration and Crop Coefficients of California 'Hass' Avocado Affected by Various Environmental and Plant Factors. *Agricultural Water Management*, 313: 109481. https://www.sciencedirect.com/science/article/pii/S0378377425001957