



# Crop coefficients and water use of young almond orchards

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## Abstract

An observational study was conducted in the northern Sacramento Valley in California, United States to determine crop water use and crop coefficients of three adjacent young Nonpareil/Monterey almond orchards. Methods used to quantify evapotranspiration estimates of crop water use include (1) a soil water balance and (2) a land surface energy balance using eddy covariance. Three adjacent almond orchards that were planted in 2016, 2017, and 2018 were monitored from 2018 to 2020. Actual crop coefficients were determined using actual evapotranspiration estimates from each orchard and short grass reference evapotranspiration from the Gerber South California Irrigation Management Information System station. Results showed that crop water use and crop coefficients increased until the 4th year, indicating the need to closely consider tree development and orchard age as factors in irrigation scheduling of young almond trees. The results led to the conclusion that farmers should use development or age-specific crop coefficients in developing orchards for irrigation scheduling until the 4th year when they can start using mature almond crop coefficients. The mid-season actual crop coefficients were 0.35, 0.55, 0.88, 1.04, and 0.99 for 1-, 2-, 3-, 4-, and 5-year-old almond orchards. This study has generated baseline data on crop water requirements of young almond orchards that could be useful for (1) developing irrigation scheduling tools for young almond orchards, and (2) determining water budgets for areas with new almond orchards.

## Introduction

California almond acreage continues to rise as more farmers are converting from annual to permanent crops such as almonds. Total almond acreage in California, including non-bearing trees, increased by 5.3% between 2019 and 2020 (United States Department of Agriculture 2020). Of the

total almond area of 647,000 hectares in California, 142,000 hectares were non-bearing almond trees in 2020 (21.9%). Management practices that optimize irrigation water use are necessary to continue to achieve profitable production of almond trees, especially in developing trees, amid increasing uncertainty in California water supplies.

Increasing acreage of almonds and uncertainty about surface water deliveries from the Sacramento-San Joaquin Delta has increased the demand for groundwater by farmers (Harter 2015). The increased reliance on groundwater for agricultural water resources led to the passage of the Sustainable Groundwater Management Act (SGMA) in 2014, with the ultimate purpose of restricting the amount of water that farmers can pump to reduce groundwater overdraft (2014). Understanding the crop water use of various crops of all developing stages is necessary for ensuring that groundwater sustainability plans accurately consider the changing irrigation water requirements for developing crops, including young almond orchards.

Optimal irrigation scheduling and water resources planning and management require information about the crop water use, also known as the evapotranspiration ( $ET$ ). The actual evapotranspiration,  $ET_a$ , is the evapotranspiration under actual field conditions and should be distinguished from the crop evapotranspiration,  $ET_c$ , which is the

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evapotranspiration of a well-watered crop under pristine conditions with no salinity, disease, or other problems that might reduce evapotranspiration (Jensen and Allen 2016). The ratio between the  $ET_c$  and the evapotranspiration of a well-watered reference crop such as grass ( $ET_0$ ), known as a crop coefficient ( $K_c$ ), can serve as a tool for irrigation scheduling of a variety of crops (Jensen and Allen 2016). Crop coefficients are primarily a function of the vegetative cover and are expected to increase as young trees grow in size (Jensen and Allen 2016). Any reduction in  $K_c$  due to water stress, salinity, disease, or reduced canopy density is referred to as an actual crop coefficient,  $K_a$  (Allen et al. 1998).

$K_a$  has been demonstrated to decline during almond harvest activities when irrigation is typically restricted, and following each irrigation event as soil water stress increases and evaporation from the soil decreases in a mature almond orchard (Bellvert et al. 2018). Almond harvest usually starts when almond orchards reach 3 years in age, so there is usually not an increase in water stress due to harvest activities in the first 2 years of growth of almond orchards. Restriction of irrigation is recommended before mechanical shaking of almond trees to reduce the risk of bark splitting.

The maximum daily transpiration of young almond trees near Córdoba, Spain has been shown to increase from 1 to 4 mm as canopy ground cover increases from 3 to 50%, confirming the need to adjust irrigation amounts as the young trees increase in size (Espadafor et al. 2015). Under- or over-irrigation of young almond orchards can influence tree health, orchard uniformity, years to full production potential, and the total cost to establish an orchard (Jarvis-Shean and Fulton 2018). Water can be lost to deep percolation by over-irrigating young almond orchards that lack rooting depth and lateral root growth (Doll and Shackel 2015). Prevention of under-irrigation throughout the growing season in young almond trees is essential for accelerating canopy and root establishment during the non-bearing years (Feres et al. 1981). Over-irrigation outside the small root zones of young almond trees can result in additional pruning and weed control requirements (Jarvis-Shean and Fulton 2018).

Research on determining  $K_c$  values for almonds has primarily focused on mature orchards. The maximum reported mid-season  $K_c$  for mature almonds has ranged between 0.90 and 1.3 (Doorenbos and Pruitt 1977; Allen et al. 1998; Sanden 2007; Allen and Pereira 2009; Goldhamer and Girona 2012; Sanden et al. 2012; Stevens et al. 2012; García-Tejero et al. 2015; Bellvert et al. 2018). Some of the reported  $K_c$  values for almonds were determined for orchards that may not have been under standard conditions of optimum soil water conditions, free of diseases, well-fertilized, and full canopy size, as suggested by Sanden et al. (2012), which explains the range in reported maximum  $K_c$  values for mature almond orchards. Another explanation for the differences in reported  $K_c$  values for almonds could be that

tree density has increased in recent years, which may have led to more light interception by the canopy compared to where the earlier  $K_c$  values were determined, as suggested by Espadafor et al. (2015).

The maximum mid-season  $K_c$  values reported by Sanden (2007), Sanden et al. (2012), Goldhamer and Girona (2012), and Bellvert et al. (2018) (1.08, 1.15, 1.17, and 1.3, respectively) were determined for almond orchards in California, United States within the last couple of decades. Actual crop coefficients,  $K_a$ , for an almond orchard in Madera County, California, United States ranged from 0.2 at Nonpareil harvest to 1.3 at full development for a mature almond orchard that experienced water stress in between irrigation events and especially leading up to harvesting activities (Bellvert et al. 2018).

Developing almond trees, which have smaller canopies and root systems, are expected to have lower  $K_c$  values than mature trees.  $K_c$  values of mature almond trees have been scaled to young almond trees using either the percent ground cover (GC) or the midday fraction of photosynthetically active radiation intercepted by the canopy (fPAR), sometimes referred to as the proportion of midday light interception. Doorenbos and Pruitt (1977) recommended a reduction in maximum  $K_c$  values by 25–35% and by 10–15% for canopies with 20 and 50% ground cover, respectively. An empirical model of  $K_c = 0.082 + 1.59 \times (\text{proportion of midday light interception})$  ( $R^2 = 0.86$ ) was determined using lysimeter data for O'Henry peach (a *Prunus* plant, like almond) and has been a valuable model for estimating site-specific  $K_c$  for irrigation scheduling and management (Ayars et al. 2003). Feres et al. (1982) determined a similarly strong relationship as Ayars et al. (2003) between percent shaded area (similar to the proportion of midday light interception) and the evapotranspiration of young almond orchards as a proportion of mature almond evapotranspiration. Espadafor et al. (2015) measured the ratio between  $K_T$  (ratio between the transpiration ( $T$ ) and  $ET_0$ ) and fPAR in 3rd and 4th year 'Guara' almond trees and found that the ratio oscillated around a value of 1.2 during the entire irrigation season from mid-May to early September. Overall, the research has demonstrated that measurements of ground cover or proportion of light interception intercepted by the canopy can be useful for developing simple models for site-specific  $K_c$  in almond.

Some recent research has focused on determining  $K_c$  for young almond orchards (younger than 5 years in age) in Spain. Water use estimates derived from a Simplified Two-Source Energy Balance Model (STSEB) for a drip-irrigated young almond orchard with 238 trees per hectare in southeast Spain from 2017 to 2019 resulted in average mid-season crop coefficients,  $K_{c,mid}$ , of 0.30, 0.33, and 0.45 for ages 2, 3, and 4 years, respectively (Sánchez et al. 2021).  $K_c$  for 4-year-old drip-irrigated young almond trees of the 'Guara' cultivar

in southwest Spain ranged between 0.4 at the beginning of the irrigation period to 1.1 during the maximum evaporative demand period in a soil water balance study using  $3\text{ m} \times 3\text{ m} \times 1\text{ m}$  drainage lysimeters (García-Tejero et al. 2015). Lysimeter data may not be representative of field conditions with potential errors of up to 200% (Allen et al. 1991). More research is needed on determining  $K_c$  of young almond orchards with high plant densities from orchard-scale studies instead of lysimeter studies.

Crop water use of young almond orchards has increased in the last several decades, partly due to increases in plant density. Seasonal evapotranspiration of drip-irrigated young almond trees was estimated in 1982 to be 51, 114, 262, 457, 643, 866, and 986 mm for 1-, 2-, 3-, 4-, 5-, 6-year-old, and mature almond trees, respectively, using a soil water balance procedure near Arbuckle, California, United States (Feres et al. 1982). The same study found a linear relationship between the percentage of area shaded by young almond trees and the evapotranspiration of young almond trees as a percentage of evapotranspiration of mature trees. Young trees with a shaded area of 10 percent in July had more than 20 percent of the evapotranspiration of mature trees, whereas 6-year-old trees shaded around 42 percent in July and had between 85 and 88 percent of the evapotranspiration of mature trees. In contrast to the Feres et al. (1982) study which involved an orchard with  $7.3\text{ m} \times 7.3\text{ m}$  tree spacing, modern almond orchards can have tighter tree spacing (for example,  $4.3\text{ m} \times 6.7\text{ m}$ ), and thus, crop water use is expected to be significantly higher in modern orchards. Young almond orchard  $ET_c$  in California, United States in 2018 was estimated to be 399, 731, and 996 mm per year in 1-, 2-, and 3-year-old orchards, respectively, which is 7.9, 6.4, and 3.8 times higher than what was estimated in 1982 (Jarvis-Shean and Fulton 2018). Updated research is needed on crop water requirements of young almond orchards to better reflect current orchard management practices.

The objectives of this study were to: (1) estimate evapotranspiration in 1- to 5-year-old almond trees using energy balance and soil water balance methods, and (2) determine crop coefficients that farmers could use for irrigation scheduling of young almond trees in California, United States.

## Materials and methods

### Study area

The study was conducted at a commercial almond orchard [*Prunus dulcis*, cultivars 75% Nonpareil and 25% Monterey], located in Corning, California ( $39.95^\circ\text{ N}$ ,  $122.13^\circ\text{ W}$ ) with rows North–South oriented. The orchards were monitored from 2018 to 2020 to determine actual evapotranspiration and crop coefficients in 1- to 5-year-old almond orchards.

The study area consisted of three adjacent orchards that were planted in 2016, 2017, and 2018, which will be referred to as P16, P17, and P18 throughout this text. The orchard sizes were 13, 8, and 14 hectares for P18, P17, and P16, respectively, as shown in Fig. 1. Row spacing was 6.7 m and tree spacing was 4.3 m, resulting in 348 trees per hectare. The tree height in the orchard planted in 2018 was 1 m in May 2018, 2 m in July 2018, 3 m in June 2019, and 4 m in May 2020. The tree height was approximately 5 m in 2020 in the orchards planted in 2016 and 2017.

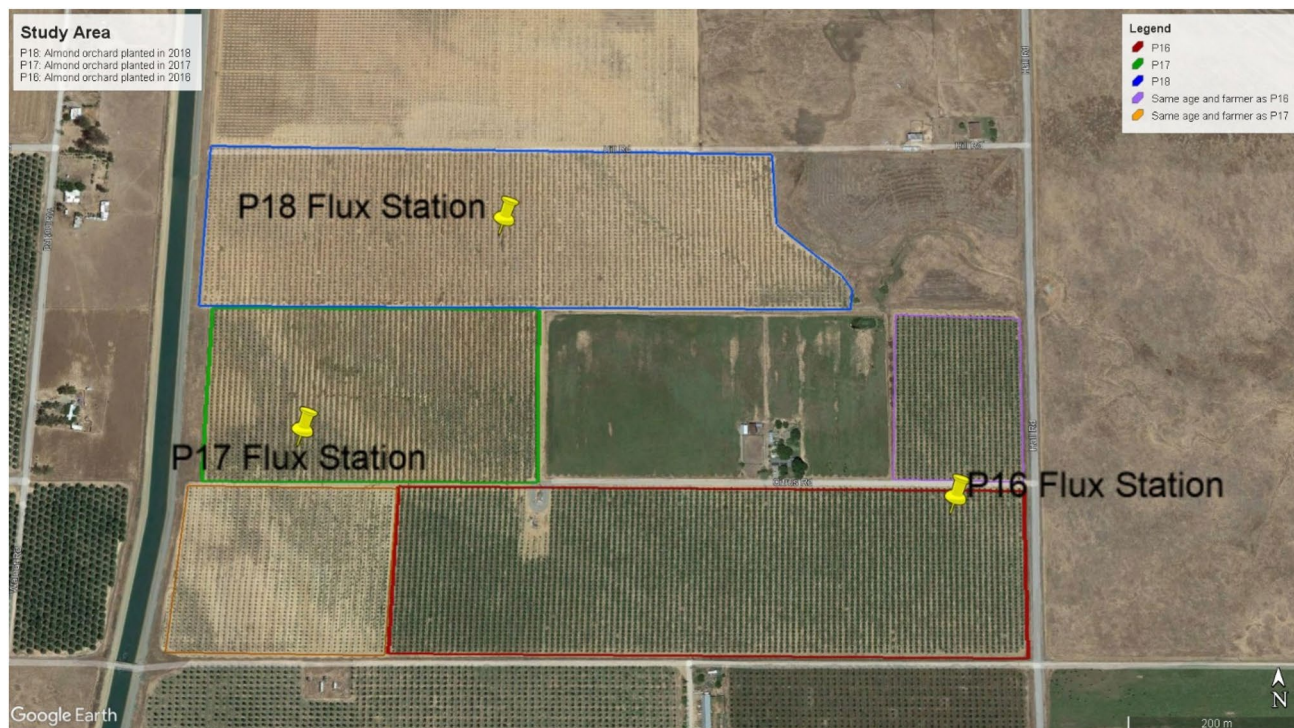
The plots were irrigated with one Olsen micro-sprinkler per tree at  $36.7\text{ L h}^{-1}$ . Each plot had a Tule station that estimated  $ET_a$  using a propriety version of the surface renewal method, which the farmer used as the primary (but not the only) basis for irrigation scheduling ([www.tuletechnologies.com](http://www.tuletechnologies.com)). The farmer also considered midday stem water potential measurements from a pressure chamber for the irrigation scheduling. The farmer implemented deficit irrigation for approximately 1 week before shaking the almond trees during harvest in the 3-, 4-, and 5-year-old trees to minimize the risk of bark splitting and improve the ease of access of the harvesting machinery. Water meter recordings were taken once a week to monitor the farmer's irrigation scheduling.

Critical growth stages for almonds include bloom in February, hull-split in July for the Nonpareil variety and in August for the Monterey variety, and harvest in August for the Nonpareil variety and September for the Monterey variety, and senescence in November. The study area has a warm-summer Mediterranean climate with mean monthly minimum and maximum temperatures of  $7.5^\circ\text{ C}$  (January) and  $26.5^\circ\text{ C}$  (July), respectively. The average annual rainfall in this region of California is 548 mm, which mainly occurs between October and May. Little to no rainfall occurs in the months leading up to almond maturity (June to September), requiring irrigation to maintain plant health and productivity. The primary soil series was Kimball loam with some sections of Perkins gravelly loam and Tehama loam (USDA NRCS National Cooperative Soil Survey). A cover crop was grown in each orchard during the fall and winter and was terminated in the spring before the peak irrigation season.

### Estimation of $ET_a$ using an energy balance

Field-scale energy flux densities were measured to evaluate the actual evapotranspiration ( $ET_a$ ) to determine the crop water use in each orchard.  $ET_a$  instead of  $ET_c$  was measured, because the orchard was commercial with occasional water stress and heterogeneity of vegetation within the orchard. Estimations of sensible heat flux density, ground heat flux density, and net radiation were used to calculate latent heat flux density as the residual of a soil-vegetation surface energy balance, as shown in Eq. 1.





**Fig. 1** Locations of the three measurement stations for determining evapotranspiration in young almond orchards near Corning, California, United States using eddy covariance energy budget method

$$\lambda E = R_n - G - H, \quad (1)$$

where  $R_n$  is net radiation [ $\text{W m}^{-2}$ ],  $G$  is ground heat flux density [ $\text{W m}^{-2}$ ],  $H$  is the sensible heat flux density [ $\text{W m}^{-2}$ ], and  $\lambda$  is the latent heat of vaporization of water [ $\text{MJ kg}^{-1}$ ]. The change in energy stored in the canopy or surface boundary layer between the ground surface and the height where  $H$  was measured, and the energy consumed by photosynthesis are usually less than a few percent of the energy balance and was assumed to be negligible (Jensen and Allen 2016). The energy balance was forced closed by assuming that  $H$  was accurately measured and solving for  $\lambda E$  as the residual of the energy balance equation shown by Eq. 1. The method of solving  $\lambda E$  as the residual of the energy balance equation obeys conservation of energy, does not require measurements of  $\lambda E$ , and has been widely discussed by other researchers (Snyder et al. 1996, 2008; Twine et al. 2000; Jensen and Allen 2016). The sensible heat flux density ( $H$ ) was measured using Eq. 2.

$$H = \rho C_p \overline{w'T'}, \quad (2)$$

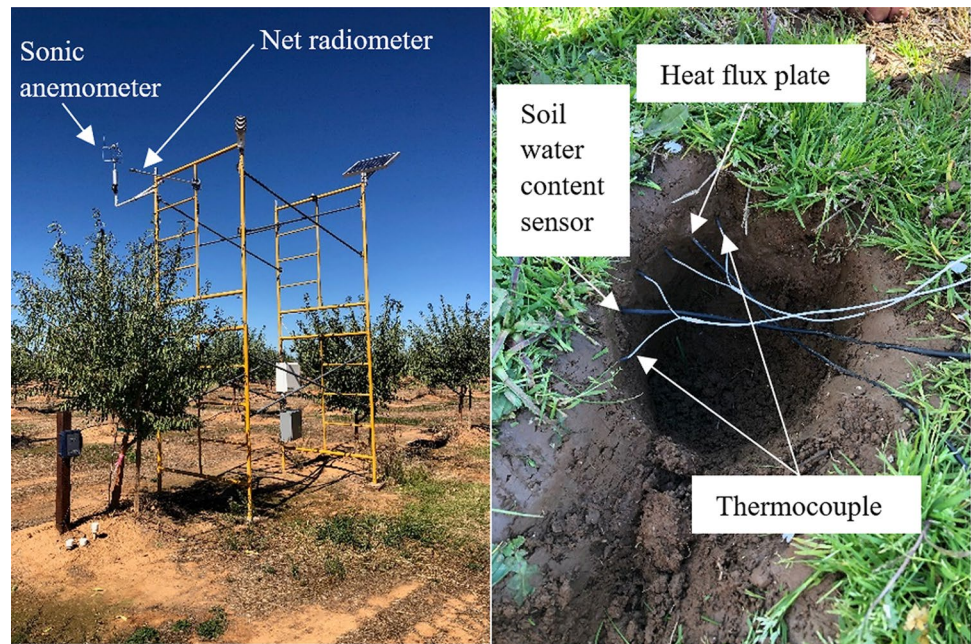
where  $w'$  is the instantaneous deviation of vertical wind velocity from the mean vertical wind velocity ( $w$ ) [ $\text{m s}^{-1}$ ],  $T'$  is the instantaneous deviation of air temperature from the mean air temperature [K],  $H$  is in  $\text{W m}^{-2}$ ,  $\rho$  is the air

density [ $\text{kg m}^{-3}$ ],  $C_p$  is the specific heat per unit mass of air at constant pressure [ $\text{J kg}^{-1} \text{K}^{-1}$ ], and the overbar represents the means of the products of the instantaneous deviations, typically over a 30-min period (Swinbank 1951; Jensen and Allen 2016).

Data from the Tule stations were not used to determine  $ET_a$  or crop coefficients as part of the objectives of this study and were only used by the farmer for irrigation scheduling. Instead,  $ET_a$  was determined using three flux stations that were installed in each of the three adjacent young almond orchards to estimate  $R_n$ ,  $G$ , and  $H$  with the purpose of using Eq. 1 to calculate  $\lambda E$ . Sensor measurements were collected with a CR3000 datalogger (Campbell Scientific, Logan, UT, USA) in each orchard in conjunction with a station-specific CRBasic program that included sensor-specific calibrations for the net radiometer and soil heat flux plates and the sonic anemometer height.

Each flux station consisted of a three-dimensional, sonic anemometer (Model 81,000 VRE, R.M. Young Company, Traverse City, MI, USA) oriented in the prevailing wind direction (north to south) and installed 1 m to 2 m above the top of the canopy on fixed scaffolding as shown in Fig. 2. The height of the sonic anemometer was 3 m in P18 at the beginning of the study in 2018 and increased to 4.6 m height in July 2019. The height of the sonic anemometer was 3.6 m in P17 in 2018 then increased to 6.5 m in 2019. The height

**Fig. 2** Left: A picture of the flux station in the 2-year-old orchard in 2019, showing the sonic anemometer and the net radiometer. Right: A picture of the soil water content sensor, heat flux plate, and thermocouples installed at 5 cm depth to measure the ground heat flux



of the sonic anemometer was 6.5 m height in P16 during the entire study. Wind speed and direction in the three directions and sonic temperature were measured at 10 Hz frequency by the sonic anemometer using serial communication in each orchard. A data table in the datalogger stored the wind velocity and sonic temperature covariance statistics required for determining  $H$  using Eq. 2. A two-dimensional coordinate rotation correction was applied to  $H$  in the datalogger program (Tanner and Thurtell 1969; Shapland et al. 2013).

Two Type E fine-wire thermocouples with 0.0762 mm diameter (FW3, Campbell Scientific, Logan, UT, USA) were installed at the same height as the sonic anemometer and measured at 10 Hz for the purpose of comparing  $H$  derived from the surface renewal method with  $H$  derived from eddy covariance as part of the quality assessment. The surface renewal method involves analyzing the energy budget of air parcels (coherent structures) that last for a short time within the crop canopy and requires high-frequency temperature measurements above the canopy (Snyder et al. 1996). The high-frequency temperature measurements above the canopy exhibit ramp-like shapes, and the amplitude and period are used to calculate  $H$  (Snyder et al. 1996). The surface renewal  $H$  was used to fill in any gaps in eddy covariance  $H$ , which were few during the study periods.

$R_n$  was directly measured in each orchard using a net radiometer (NR-LITE2, Campbell Scientific, Logan, UT, USA) that measured the net incoming shortwave and longwave infrared radiation in relation to the reflected outgoing shortwave and longwave infrared radiation at 1 s scan rate. The net radiometer was cleaned in May or June of each year of the study.

$G$  was determined in each orchard using measurements from three soil heat flux plates at 5 cm depth in each orchard at 1 s scan rate (HFT3.1, REBS, Bellevue, WA, USA). The three heat flux plates were located (1) at one location wetted at the soil surface by the irrigation near the sprinkler, (2) at a location not wetted at the soil surface by the irrigation further away from the sprinkler, and (3) at a location in between tree rows where there was cover crop in the spring. The soil heat flux measurements were adjusted by the change in heat storage within the soil layer above the plates ( $\Delta S$ ) to model the ground heat flux at the surface which may be different than at the 5 cm measurement depth using the method described by Shapland et al. (2013). Determination of  $\Delta S$  required measurements of soil water content at 5 cm depth (EC5, METER Group, Pullman, WA, USA) and soil temperature from thermocouples in the 0–5 cm layer above the plates at 1 s scan rate (TCAV-L, Campbell Scientific, Logan, UT, USA).

Auxiliary data at 1 s scan rate included air temperature and relative humidity (HMP45C, Campbell Scientific, Logan, UT, USA).

$H$ ,  $R_n$ ,  $G$ , and auxiliary data were averaged to a 30-min interval in the CRBasic datalogger program. A Microsoft Excel spreadsheet program was used to calculate  $\lambda E$  as the residual of the energy balance of the land surface using Eq. 1 and the half-hourly  $H$ ,  $R_n$ , and  $G$  data outputted from the datalogger (Shapland et al. 2013).  $\lambda E$  was converted into half-hourly and daily evapotranspiration,  $ET_a$ , measurements in  $\text{mm day}^{-1}$  using the latent heat of vaporization in the Microsoft Excel spreadsheet program.

Three infrared gas analyzers were not within the budget of this study, so the residual approach of the energy balance



using Eq. 1 was used to estimate  $\lambda E$ . Although evapotranspiration can be estimated using measurements of latent heat flux density,  $\lambda E$ , using the eddy covariance method, the requirement of an expensive quick-response infrared gas analyzer limits the practical use of that method. Computing  $\lambda E$  as the residual of the soil-vegetation surface energy balance removes the need for an infrared gas analyzer but requires estimation or assumption of all other components in the energy balance of the soil-vegetation surface (Snyder et al. 1996, 2008; Twine et al. 2000; Shapland et al. 2013; Jensen and Allen 2016).

Large orchards were selected to provide enough fetch to estimate  $ET$  using each flux station under conditions of various incoming wind directions, as shown by Fig. 1. The predominant wind directions were north to south and south to north. The footprint of the P16 flux measurements sometimes included space from the orchard directly to the north of P16 (three hectares), which was the same age as P16 and managed by the same farmer. Likewise, the footprint of the P17 flux measurements sometimes included space from the orchard directly to the south of P17 (five hectares), which was the same age as P17 and managed by the same farmer. The available fetch distances of the flux stations were 100 m, 160 m, and 240 m from the north edge of an orchard of the same age and grower in P18, P17, and P16, respectively, and 170 m, 480 m, and 325 m from the south edge of an orchard of the same age and grower in P18, P17, and P16, respectively. A flux footprint model (Kljun et al. 2015) using wind direction and micro-meteorological data verified adequate fetch of the footprint area within each orchard in the predominant incoming wind directions. The Kljun et al. (2015) model showed that the footprint area near the sensors in the upwind direction influence the flux measurements the most, and rapidly decreases in contribution to the measured fluxes the further away from the sensors. Any footprint contributions to the flux measurements that extended beyond each orchard were small in comparison to the footprint contributions from the space within the available fetch of each flux station.

### Estimation of $ET_a$ using a soil water balance

Seasonal  $ET_a$  was estimated using a soil water balance, as shown in Eq. 3

$$ET_a = P + I + Q_i - Q_o - \Delta S, \quad (3)$$

where  $P$  is precipitation [mm],  $I$  is irrigation [mm],  $Q_i$  is the inflow besides  $P$  and  $I$  [mm],  $Q_o$  is the outflow besides  $ET_a$  [mm], and  $\Delta S$  is the change in soil water storage during the period used for assessing the water balance [mm] for a specific period during the growing season. The irrigation amount was determined by two flow meters (which were

averaged) in each orchard. Neutron counts were measured at the beginning of the irrigation season and immediately before the Monterey harvest in mid-September in 2019 and 2020 and converted into volumetric soil water content using a calibration equation obtained from the same region. The  $\Delta S$  was determined as the change in volumetric soil water content between the beginning of the irrigation season and immediately before harvest.  $Q_i$  includes lateral inflow and upward flow from the water table, which were considered negligible.  $Q_o$  includes surface runoff, subsurface lateral outflow, and vertical drainage. Surface runoff was observed to be negligible as expected for micro-sprinkler irrigation and considering that the farmer was irrigating to match the evapotranspiration measured by the Tule system in each respective orchard. Minimal rainfall occurred during the major periods of the study and was measured by a metric tipping bucket rain gauge with a 24.5 cm orifice (TE525MM, Campbell Scientific, Logan, UT, USA) at the Gerber South CIMIS (California Irrigation Management Information System) station ID 222.

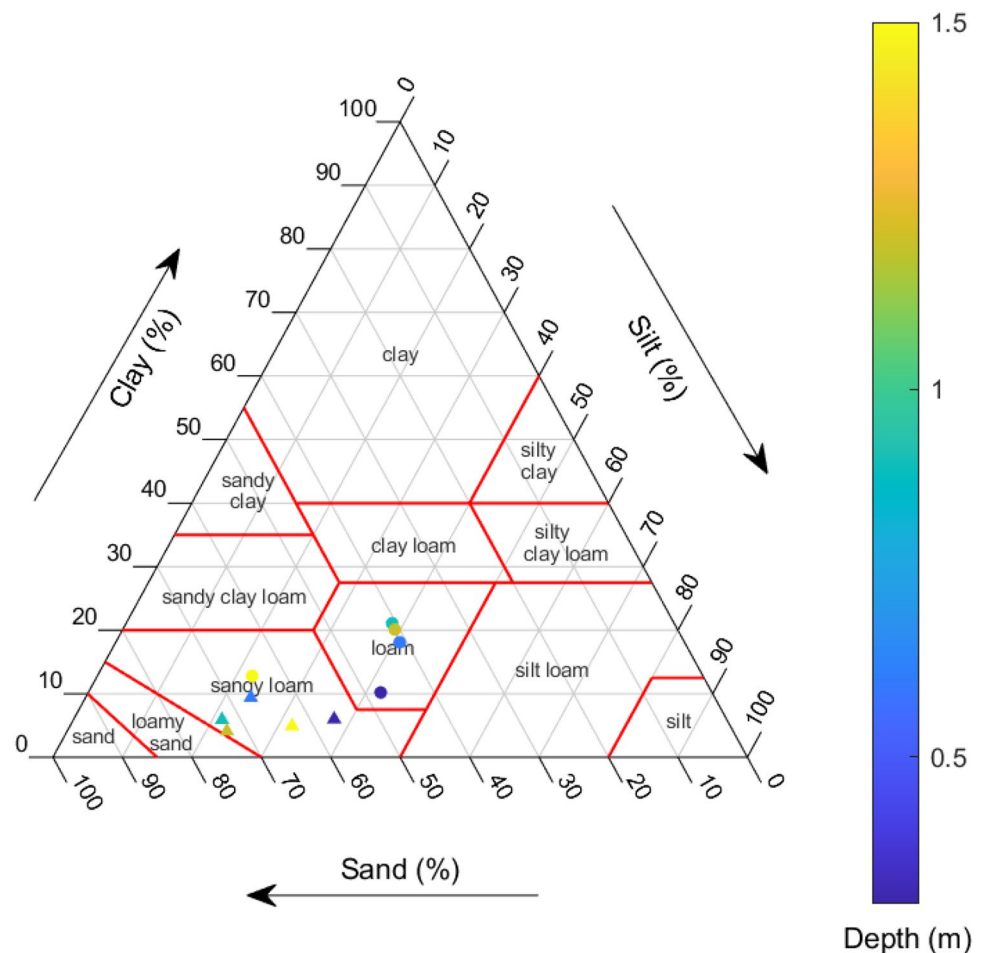
The neutron probe access tubes were installed using a Geoprobe (Salina, KS, USA) in the orchards planted in 2017 and 2018. Four transects of access tubes were installed in each of the two orchards. In each transect, two access tubes were installed 90 and 180 cm from the tree trunk into the row to the east, two access tubes were installed at 90 and 180 cm from the tree trunk along the tree row to the north, and two access tubes were installed at 90 and 180 cm from the tree trunk along the tree row to the south. The neutron probe data showed that the soil water content decreased throughout the periods of the soil water balance calculations, so drainage was considered negligible. The field capacity in the top 240 cm is  $0.28 \text{ m}^3 \text{ m}^{-3}$  and the permanent wilting point in the top 240 cm is  $0.12 \text{ m}^3 \text{ m}^{-3}$ . The soil texture was analyzed using the pipette method at 0–30, 30–60, 60–90, 90–120, 120–240 cm sections at the same locations that the soil was excavated for installing the access tubes and the results are shown in Fig. 3 (Soil Survey Staff 1992). The soil texture was primarily sandy loam, loam, and loamy sand in P18 and sandy loam, clay loam, silt loam, and loam in P17. Most of the change in soil water content was driven by root water uptake in response to irrigation events.

### Estimation of crop coefficients

Actual crop coefficients,  $K_a$ , were calculated as the ratio between  $ET_a$  and the reference evapotranspiration from a standard well-watered grass surface ( $ET_o$ ) as shown in Eq. 4.

$$K_a = \frac{ET_a}{ET_o}, \quad (4)$$

**Fig. 3** Soil texture of the orchards planted in 2017 (P17) and 2018 (P18) measured using the pipette method expressed as averages of 48 samples at 0–30 cm, 30–60 cm, 60–90 cm, 90–120 cm, and 120–150 cm soil layers



where  $ET_a$  is the actual evapotranspiration,  $ET_o$  is the grass reference evapotranspiration, and  $K_a$  is the actual crop coefficient.  $ET_o$  of a grass reference surface was obtained from the CIMIS Gerber South Station ID 222 (40.028778° N, 122.15575° W), located approximately 9.6 km from the flux stations used in this study. The ASCE Penman–Monteith method was used to estimate hourly  $ET_o$  (Jensen and Allen 2016).

Net radiation varies with cloud cover.  $K_a$  should only be estimated when the net radiation is similar between the locations where  $ET_o$  and  $ET_a$  are estimated, especially on days when there are ephemeral clouds. Solar radiation [ $\text{MJ m}^{-2} \text{d}^{-1}$ ],  $R_{s,CIMIS}$ , instead of net radiation [ $\text{MJ m}^{-2} \text{d}^{-1}$ ] was measured at the CIMIS Gerber South Station ID 222. Ideally, net radiation should be measured at both sites, but only solar radiation was available at the CIMIS Gerber South Station ID 222. The  $K_a$  was only estimated when the ratio of  $R_{s,CIMIS}$  and the net radiation at the  $ET_a$  station was between 0.2 and 0.7 to make sure that the net radiation was similar between the sites where  $ET_o$  and  $ET_a$  were estimated, resulting in gaps in the daily  $K_a$ . The daily  $K_a$  was ignored when

the daily precipitation was more than 1 mm. The gaps in daily  $K_a$  were filled by adding the  $K_a$  of the day before the gap to the difference of the  $K_a$  of the 2 days around the gap, up to a maximum gap of 6 days.

Full canopy size was observed in late May to early June in each year and orchard.  $K_{a,mid}$  was calculated as the average  $K_a$  from June 1 to August 31 within the same calendar year in the 1- and 2-year-old orchards. In the 3-, 4-, and 5-year-old orchards,  $K_{a,mid}$  was calculated as the average  $K_a$  from June 1 to July 31 within the same calendar year to eliminate the effects of water stress from harvest activities that reduced the  $K_a$ . Averages of  $K_{a,mid}$  were calculated of the 2-year-old orchards in 2018 and 2019 (P17 and P18, respectively), the 3-year-old orchards in 2019 and 2020 (P17 and P18, respectively), and the 4-year-old orchards in 2019 and 2020 (P16 and P17, respectively) in the final reported  $K_{a,mid}$ .

### Auxiliary plant and soil measurements

The fraction of photosynthetically active radiation intercepted by the canopy (fPAR) was determined using a

**Table 1** Fraction of photosynthetically active radiation intercepted by the canopy in relation to orchard age

Orchard	Age	Date	Average fPAR
P18	2 years	5 June 2019	0.09
P17	3 years	5 June 2019	0.23
P16	4 years	5 June 2019	0.47
P18	3 years	19 June 2020	0.25
P17	4 years	19 June 2020	0.22
P16	5 years	19 June 2020	0.55

mule lightbar to gain insight on differences in canopy size between the three orchards (Lampinen et al. 2012; Zarate-Valdez et al. 2012). The fPAR of 7 to 14 rows in each orchard were averaged to determine a single fPAR estimate in each orchard in 2019 and 2020, as shown in Table 1.

Midday stem water potential was measured at three trees (using one leaf per tree) near each of the flux measurement stations in each orchard using a pressure chamber (3005 Series Plant Water Status Console, Soil Moisture Co., Santa Barbara, California, United States). Measurements were done once a week during the irrigation season in all years of the study.

**Table 2** Monthly average solar radiation ( $R_s$  in  $W\ m^{-2}$ ), monthly average air temperature ( $T_{a,mean}$  in  $^{\circ}C$ ), monthly average relative humidity ( $RH_{avg}$  in %), monthly average wind speed 1 to 2 m above the canopy ( $u$  in  $m\ s^{-1}$ ), average minimum relative humidity ( $RH_{avg,min}$  in %), and monthly average vapor pressure ( $e$  in kPa) at the young almond orchard planted in 2018 near Corning, California, United States and monthly cumulative grass reference evapotranspiration ( $ET_o$  in mm) and monthly cumulative rainfall in mm from the Gerber South CIMIS station in 2018–2020

	$R_s$ ( $W\ m^{-2}$ )	$T_{a,mean}$ ( $^{\circ}C$ )	$RH_{avg}$ (%)	$u$ ( $m\ s^{-1}$ )	$RH_{avg,min}$ (%)	Rainfall (mm)	$e$ (kPa)	$ET_o$ (mm)
2018								
June	280	27.5	38.3	3.6	20.1	3	1.2	230
July	241	28.0	47.6	1.7	23.3	0	1.7	212
August	205	24.1	55.1	1.2	27.1	0	1.5	166
September	183	21.8	46.0	1.4	21.2	0	1.1	152
October	130	18.2	47.9	2.0	26.3	12	0.9	116
2019								
June	271	25.1	45.4	2.0	22.5	0	1.4	225
July	259	26.4	49.7	1.5	26.2	0	1.6	211
August	227	26.1	50.7	1.5	25.7	0	1.6	189
September	179	21.7	50.4	2.0	25.7	8	1.2	149
October	143	16.4	36.4	2.4	15.7	0	0.6	130
2020								
January	60	8.9	82.3	2.3	61.1	33	0.9	38
February	121	11.6	51.8	2.6	27.1	0	0.7	88
March	139	11.7	63.6	2.5	40.2	57	0.8	95
April	199	16.4	57.7	1.9	33.1	11	1.0	135
May	219	20.0	54.0	2.1	30.3	51	1.2	175
June	255	24.2	47.1	1.6	24.9	5	1.4	211
July	257	26.5	47.4	1.2	25.5	0	1.5	222
August	188	26.4	51.7	1.0	27.0	2	1.7	166
September	142	24.1	49.5	1.1	23.6	0	1.4	144

## Results

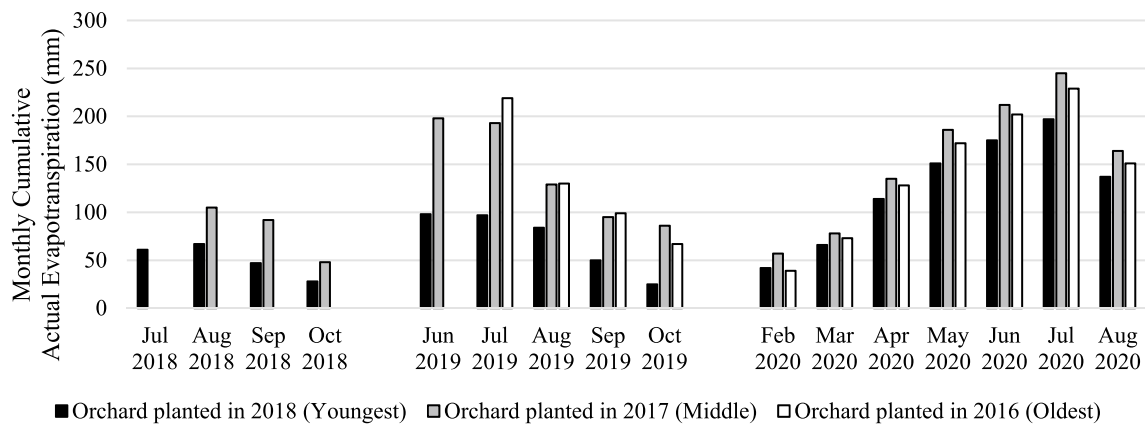
### Agro-meteorological conditions

Monthly average or cumulative agro-meteorological data at the study site and reference evapotranspiration ( $ET_o$ ) from a grass reference surface calculated using the Penman–Monteith equation from the Gerber South CIMIS station from 2018 to 2020 are shown in Table 2. The agro-meteorological conditions, including solar radiation, air temperature, relative humidity, vapor pressure, wind speed, and crop water use by the reference grass crop were similar across all periods of the study. The similarity across all 3 years of the study provides a satisfactory opportunity for comparing evapotranspiration in the young almond orchards as they increased in age without variations in agro-meteorological conditions being a major factor.

### Daily and seasonal evapotranspiration

The monthly actual evapotranspiration ( $ET_a$ ) of each orchard from 2018 to 2020 is shown in Fig. 4 as determined by the eddy covariance energy budget method. In every year of the study, monthly  $ET_a$  was higher in the older orchards except in 2020 when the 4-year-old orchard had higher monthly  $ET_a$





**Fig. 4** Monthly cumulative crop water use ( $ET_a$ ) [mm] of young almond trees measured using an eddy covariance energy balance in the orchards planted in 2016 (P16), 2017 (P17), and 2018 (P18) in

2018–2020. Note on gaps in data: The study periods were July 2018 to October 2018, June 2019 to October 2019, and February 2020 to September 2020

(245 mm in July) than the 5-year-old orchard (229 mm in July). Lower  $ET_a$  could be the result of differences in water stress, vegetation, or canopy size. The average midday stem water potential was  $-1.1$  and  $-1.3$  MPa in July and August in the 4-year-old orchard (P17) in 2020, which demonstrated less water stress than the average midday stem water potential of  $-1.5$  and  $-1.7$  MPa in July and August in the 5-year-old orchard (P16) in 2020. The average fPAR was higher in the 5-year-old orchard (0.55) than the 4-year-old orchard (0.22) in 2020, suggesting a greater canopy size in the older orchard. The increased water stress explains the lower  $ET_a$  in the 5-year-old orchard compared to the 4-year-old orchard in July and August of 2020, whereas the fPAR observations do not explain the difference. The average midday stem water potential was similar between the 4-year-old and 5-year-old orchards in May, June, and September ( $-0.9$ ,  $-1.1$ , and  $-1.1$  MPa in the 4-year-old orchard and  $-1.0$  MPa in all 3 months in the 5-year-old orchard), suggesting no contribution from water stress in explaining differences in  $ET_a$  in those months.

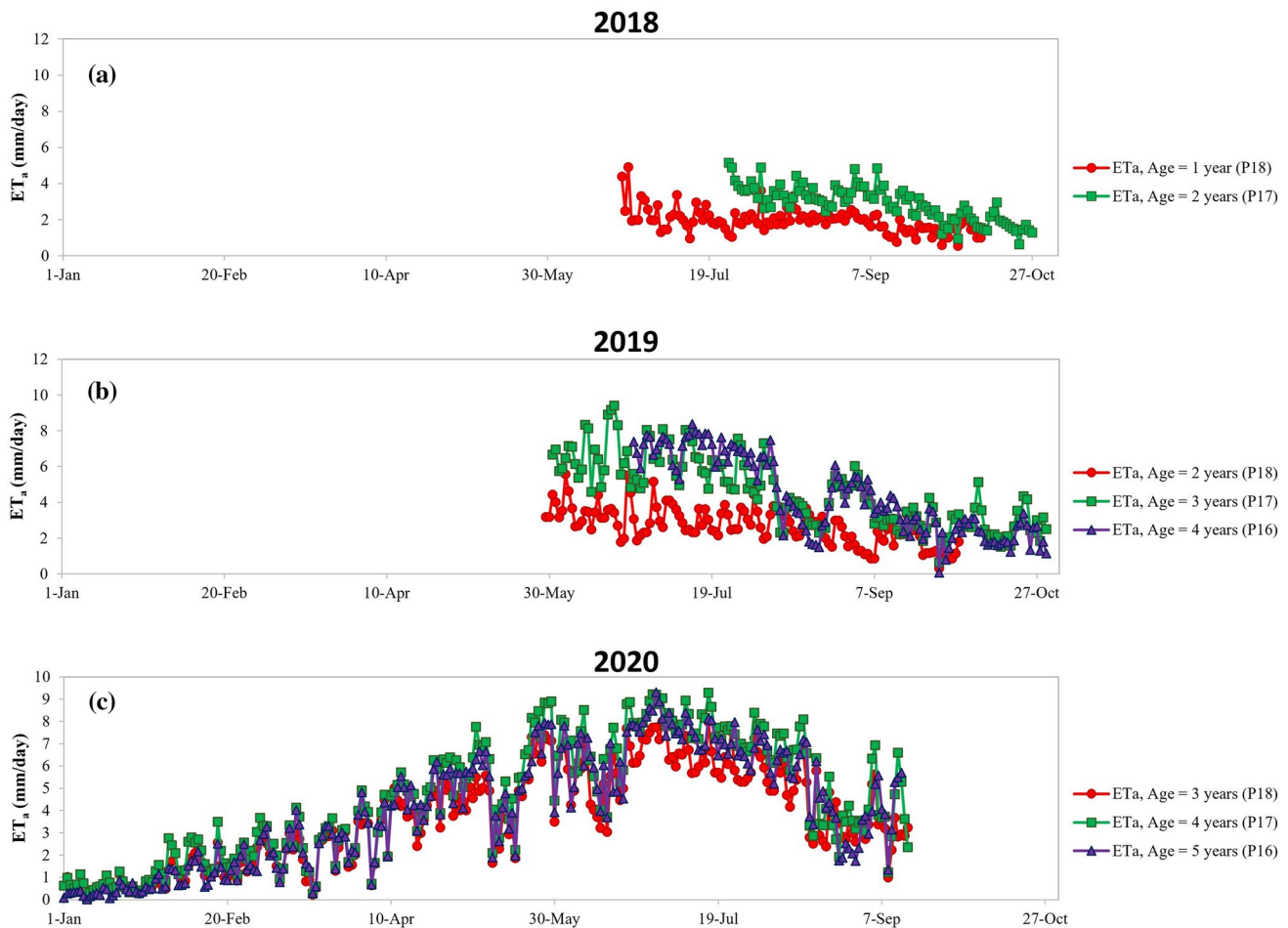
Figure 5a shows the daily  $ET_a$  [ $\text{mm day}^{-1}$ ] of 1- and 2-year-old almond orchards in 2018 measured using the eddy covariance energy balance method. The 2-year-old trees had higher daily  $ET_a$  than the 1-year-old trees in June through September. Normally, almond farmers reduce irrigation during the week leading up to the harvests of each variety in August and September to reduce damage to tree trunks and to improve orchard access of the harvest machinery, which would reduce  $ET_a$  and increase water stress. The farmer normally continues to withhold irrigation for a couple of weeks after harvest while the almonds are drying on the ground, which also contributes to water stress and a reduction in  $ET_a$ . However, neither the 1-year-old nor 2-year-old trees were harvested using a mechanical shaker to avoid damaging the tree trunks of the developing trees. The 1- and 2-year-old

orchards approached similar daily  $ET_a$  at the end of September and early October as the leaves progressed into senescence and atmospheric evaporative demand decreased. By mid-October, the daily  $ET_a$  was again higher in the 2-year-old orchard than in the 1-year-old leaf orchard.

Figure 5b shows the daily  $ET_a$  [ $\text{mm day}^{-1}$ ] of 2-, 3-, and 4-year-old almond orchards in 2019 measured using the eddy covariance energy balance method. The 2-year-old almond orchard had the lowest daily  $ET_a$ . The 3- and 4-year-old orchards had similar daily  $ET_a$  except in July when the 4-year-old orchard had higher daily  $ET_a$  than the 3-year-old orchard. Both the 3- and 4-year-old orchards were harvested using a mechanical shaker in August for the Nonpareil trees and September for the Monterey trees. The farmer reduced irrigation in August during the harvest activities, so the  $ET_a$  declined in the 3- and 4-year-old orchards.

Water stress noticeably reduced daily  $ET_a$  in the 3- and 4-year-old orchards in 2019 during the harvest activities. The midday stem water potential decreased from  $-1.2$  MPa on August 7, 2019, to  $-1.5$  MPa on August 13, 2019, to  $-2.0$  MPa on August 21, 2019, during the period when irrigation was reduced during harvest activities in the 3-year-old orchard in 2019, corresponding with the reduction in daily  $ET_a$  during August. Midday stem water potential increased to  $-1.4$  MPa on September 18, 2019, and  $-0.9$  MPa on September 27, 2019, after harvest activities concluded and irrigation continued. The grower did not appear to reduce irrigation for the Monterey trees in the 3-year-old orchard in 2019.

The midday stem water potential decreased from  $-1.5$  MPa on August 7, 2019, to  $-2.4$  MPa on August 13, 2019, to a severe  $-3.1$  MPa on August 21, 2019, during the period when irrigation was reduced during harvest activities in the 4-year-old orchard in 2019. This corresponds to the same period when daily  $ET_a$  decreased during August, similar to in the 4-year-old orchard in 2019. After the



**Fig. 5** **a** Daily crop water use ( $ET_a$ ) in  $\text{mm day}^{-1}$  of 1- and 2-year-old almond orchards in 2018 near Corning, California, United States measured using an eddy covariance energy balance. **b** Daily crop water use ( $ET_a$ ) in  $\text{mm day}^{-1}$  of 2-, 3-, and 4-year-old almond orchards in 2019 near Corning, California, United States measured

using an eddy covariance energy balance. **c** Daily crop water use ( $ET_a$ ) in  $\text{mm day}^{-1}$  of 3-, 4-, and 5-year-old almond orchards in 2020 near Corning, California, United States measured using an eddy covariance energy balance

Nonpareil harvest, the midday stem water potential increased to  $-1.4$  MPa on September 4, 2019, and to  $-1.1$  MPa on September 11, 2019, before decreasing to  $-1.8$  MPa during the Monterey harvest on September 27, 2019. The 2-year-old orchard was not mechanically shaken to avoid damaging the tree trunks, so there was no decrease in  $ET_a$  during August.

Figure 5c shows the daily  $ET_a$  [ $\text{mm day}^{-1}$ ] of 3-, 4-, and 5-year-old almond orchards in 2020 measured using the eddy covariance energy balance method. Both the 4- and 5-year-old orchards had similar daily  $ET_a$ , with the 4-year-old orchard typically slightly above the 5-year-old orchard. The 3-year-old orchard had the lowest daily  $ET_a$ . Daily  $ET_a$  increased beginning in January and peaked in all three orchards in July before decreasing as the atmospheric evaporative demand lowered in August through October and leaves began to fall due to harvest activities and senescence. All three orchards were harvested with a mechanical shaker in August for the Nonpareil trees and September for the

Monterey trees. The farmer reduced irrigation during August and September to prepare for the harvest activities, resulting in a reduction in  $ET_a$ . This reduction in  $ET_a$  corresponded with considerable water stress near the Nonpareil harvest on August 26, 2020, with midday stem water potential at  $-1.4$ ,  $-1.8$ , and  $-2.8$  MPa in the 3-, 4-, and 5-year-old orchards. The farmer continued irrigation in early September, which resulted in midday stem water potential at  $-0.5$ ,  $-0.7$ , and  $-0.9$  MPa on September 9, 2020, before decreasing to  $-1.2$ ,  $-1.6$ , and  $-1.2$  MPa on September 16, 2020, in the 3-, 4-, and 5-year-old orchards, respectively, near the Monterey harvest activity when the farmer reduced irrigation again and when  $ET_a$  decreased. Also, smoke from the LNU Lightning Complex Fires between August 17, 2020 and the end of September reduced net radiation, which also contributed to a decline in  $ET_a$ .

Table 3 shows results of the soil water balance for the period April 12, 2019, to July 12, 2019, in the 2- and 3-year-old orchards, representing the crop water use of the spring to

**Table 3** Soil water balance for the period April 12, 2019, to July 12, 2019

	Orchard planted in 2018 (2-year-old)	Orchard planted in 2017 (3-year-old)
Irrigation (mm)	149	234
Rainfall (mm)	85	85
$\Delta$ Soil water (mm)	– 81	– 164
Evapotranspiration (mm)	315	484

mid-summer period. The grower applied 149 mm of irrigation to the 2-year-old orchard and 234 mm of irrigation to the 3-year-old orchard, indicating that he intended to irrigate the older trees with more water. The soil water content decreased by 81 mm and 164 mm in the 2- and 3-year-old orchards, respectively, during the period. The crop water use was 315 mm in the 2-year-old orchard and 484 mm in the 3-year-old orchard.

Table 4 shows results of the soil water balance for the period of July 12, 2019 to September 10, 2019 (in the 3-year-old orchard), and July 12, 2019 to September 18, 2019 (in the 4-year-old orchard), representing the late summer period. The soil water content measurements for the two orchards were done on different days in mid-September due to labor availability (8 days apart). The 8 mm rainfall in the orchard planted in 2018 occurred on September 16, 2019. The grower applied approximately the same amount of water to both ages of orchards, 147 mm in the 2-year-old orchard and 142 mm in the 3-year-old orchard. Despite approximately the same amount of irrigation water applied, the soil water content decreased more in the 3-year-old orchard than in the 2-year-old orchard—81 mm versus 29 mm—likely due to larger canopy sizes and root systems in the 3-year-old orchard. The crop water use was higher in the 3-year-old orchard than in the 2-year-old orchard—223 mm versus 184 mm.

Table 5 shows the soil water balance for the period February 26, 2020, to September 16, 2020, in the 3- and 4-year-old orchards. The grower applied 672 mm of irrigation to the 3-year-old orchard and 725 mm of irrigation to the 4-year-old orchard, indicating that he irrigated the older trees more than the younger trees and increased the irrigation amount compared to 2019 in both orchards. The soil water content decreased by 19 mm in the 3-year-old orchard whereas the soil water content decreased by 175 mm in the 4-year-old orchard. The net result was 817 mm of crop water use in the 3-year-old orchard and 1026 mm of crop water use in the 4-year-old orchard.

Table 6 compares the seasonal  $ET_a$  estimates using a soil water balance method versus an eddy covariance energy balance method. Seasonal  $ET_a$  estimates were in close agreement between the two methods with percent errors ranging

**Table 4** Soil water balance between July 12, 2019, and mid-September of 2019

	Orchard planted in 2018 (2-year-old)	Orchard planted in 2017 (3-year-old)
Irrigation (mm)	147	142
Rainfall (mm)	8	0
$\Delta$ Soil water (mm)	– 29	– 81
Evapotranspiration (mm)	184	223

The soil water balance was computed for the period of July 12, 2019, to September 10, 2019 in the orchard planted in 2017, and for the period July 12, 2019 to September 18, 2019 for the orchard planted in 2018

**Table 5** Soil water balance between February 26, 2020, and September 16, 2020

	Orchard planted in 2018 (3-year-old)	Orchard planted in 2017 (4-year-old)
Irrigation (mm)	672	725
Rainfall (mm)	125	125
$\Delta$ Soil water (mm)	– 19	– 175
Evapotranspiration (mm)	817	1026

between -20% and 5% for the different periods analyzed. A shorter sample interval may have contributed to an increased percent error in the soil water balance derived  $ET_a$  estimate of the 3-year-old orchard during the July 15, 2019, to September 10, 2019 period.

Cumulative crop water use was measured through the eddy covariance energy budget method in 3-, 4-, and 5-year-old almond trees in 2020 starting from peak bloom. The cumulative  $ET_a$  from full bloom until September 11 (around the end of harvest activities) was 888, 1075, and 995 mm in the 3-, 4-, and 5-year-old orchards, respectively, in 2020. The cumulative  $ET_a$  was 21% higher in the 4-year-old orchard than in the 3-year-old orchard, 12% higher in the 5-year-old orchard than in the 3-year-old leaf orchard, and 8% lower in the 5-year-old orchard than in the 4-year-old orchard. Increased water stress may have resulted in lower cumulative  $ET_a$  in the 5-year-old orchard than in the 4-year-old orchard, indicating that age is not the only factor to consider for irrigation scheduling.

### Daily and mid-season actual crop coefficients ( $K_a$ )

Figure 6a shows the daily actual crop coefficients ( $K_a$ ) for 1- and 2-year-old orchards in 2018. Daily  $K_a$  was consistently higher in the 2-year-old orchard than in the 1-year-old



**Table 6** Comparison of seasonal evapotranspiration estimates

Field	Age	Period	ET <sub>a</sub> (mm) Soil water balance	ET <sub>a</sub> (mm) Energy balance	Percent error
P18	2 years	July 12, 2019 to September 18, 2019	184	175	5%
	3 years	February 26, 2020 to September 16, 2020	817	899	– 10%
P17	3 years	July 15, 2019 to September 10, 2019	223	268	– 20%
	4 years	February 26, 2020 to September 16, 2020	1026	1090	– 6%

orchard, indicating the need to use crop coefficients according to age or development to schedule irrigation through crop water use replacement. Spikes in the  $K_a$  throughout the season aligned with irrigation events. Daily  $K_a$  considerably increased from 1 October 2018 to 5 October 2018 when there was low  $ET_o$  on those days. Daily  $K_a$  was smoother when the  $ET_o$  was also smoother. When  $ET_o$  decreases,  $ET_a$  theoretically should decrease accordingly because the environmental conditions that drive  $ET_o$  also drive  $ET_a$ .

Figure 6b shows the daily actual crop coefficients ( $K_a$ ) for 2-, 3-, and 4-year-old orchards in 2019. Daily  $K_a$  was consistently higher in the 3- and 4-year-old orchards than in the 2-year-old orchard. The  $K_a$  declined between 07 August 2019 and 27 August 2019 due to the farmer's reduction in irrigation during the harvest activities, which aligned with the decrease in midday stem water potential previously discussed in the daily  $ET_a$  results.

Figure 6c shows the daily actual crop coefficients ( $K_a$ ) for 3-, 4-, and 5-year-old orchards in 2020. Daily  $K_a$  was the lowest in the 3-year-old orchard. In 2020, the 4-year-old orchard sometimes had a higher daily  $K_a$  than the 5-year-old orchard, indicating that age is not the only development factor that affects the crop coefficient. Like in 2019, daily  $K_a$  decreased between 16 August 2020 and 04 September 2020 and near 09 September 2020 due to a reduction in irrigation during harvest activities (in the Nonpareil and Monterey varieties, respectively), which aligned with the reduction in  $ET_a$  and midday stem water potential. The reduction in daily  $K_a$  during this period was lower in 2020 than in 2019, because the farmer irrigated more in 2020 before harvest to avoid the severe water stress that occurred in 2019 during the harvest period.

### Mid-season crop coefficients as a function of orchard age

The mid-season actual crop coefficients,  $K_{a,mid}$ , were 0.35, 0.55, 0.88, 1.04, and 0.99 for 1-, 2-, 3-, 4-, and 5-year-old almond orchards.  $K_{a,mid}$  increased until the 4th year.  $K_{a,mid}$  decreased at the 5th year, indicating that factors other than age, such as canopy size, vegetation, and water stress, can affect the  $K_{a,mid}$ . The reported  $K_{a,mid}$  values were averages of the 2-year-old orchards in 2018 and 2019 (P17 and P18,

respectively), the 3-year-old orchards in 2019 and 2020 (P17 and P18, respectively), and the 4-year-old orchards in 2019 and 2020 (P16 and P17, respectively). Only one replicate of  $K_{a,mid}$  was available for the 1- and 5-year-old orchards, so there is more uncertainty regarding those ages.

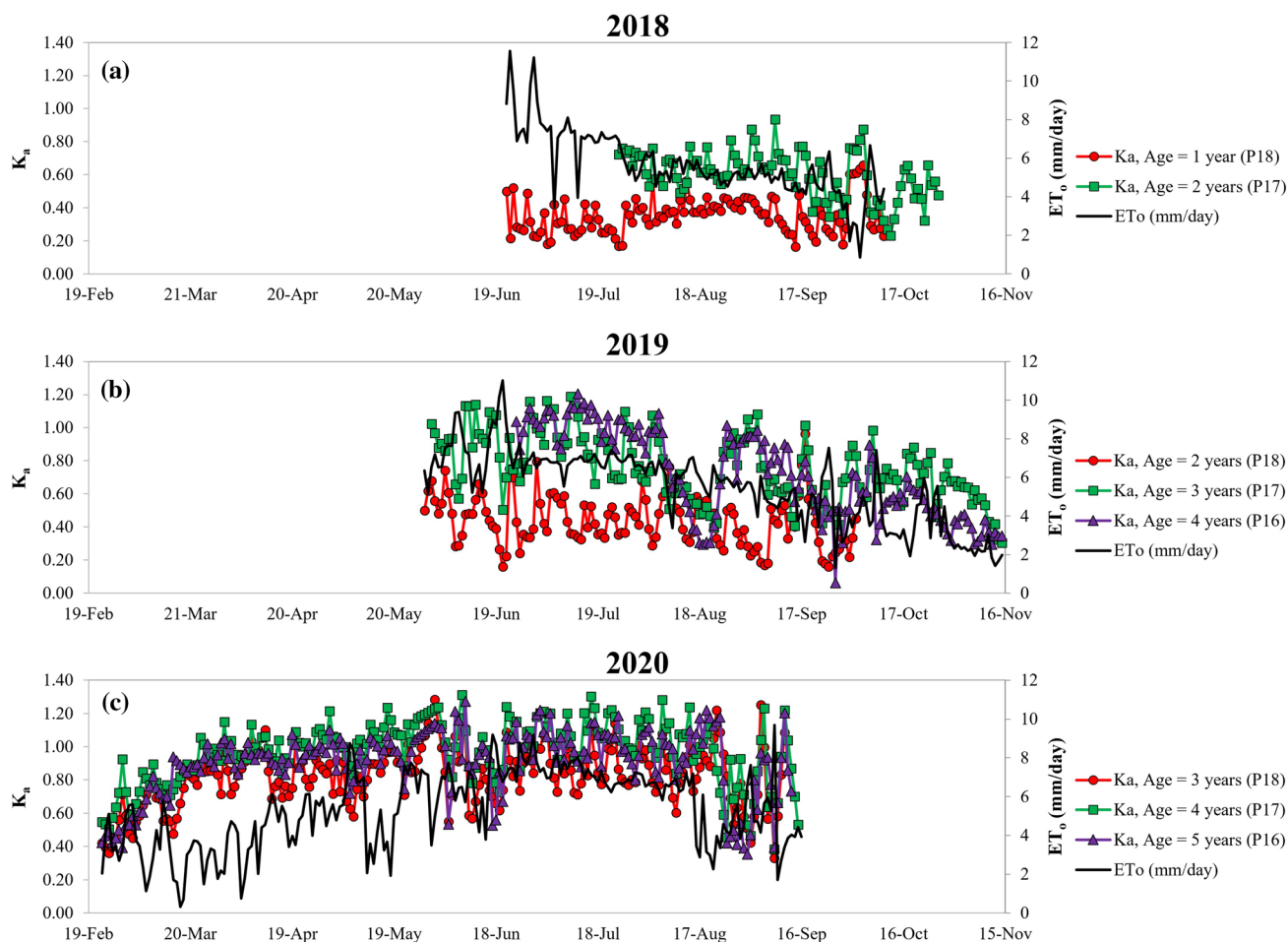
Figure 7 shows a regression between  $K_{a,mid}$  and orchard age from 1- to 5-year-old [ $K_{a,mid} = -0.0501(\text{Age})^2 + 0.4882 \times \text{Age} - 0.1526$ ]. The correlation between orchard age and  $K_{a,mid}$  is excellent ( $R^2 = 0.92$ ) and the curve flattened when the age reached 4th and 5th year. Overall, 92% of the variability in  $K_{a,mid}$  was explained by the age of the orchard. The 2<sup>nd</sup> order polynomial suggests a maximum  $K_{a,mid}$  at 4.9 years before decreasing, which is contrary to the expectation that  $K_{a,mid}$  would reach a steady state as the age approaches maturity, indicating that factors other than age, such as the canopy size or water stress may explain the remaining 8% of the variability in  $K_{a,mid}$ .

### Crop coefficients as a function of radiation interception

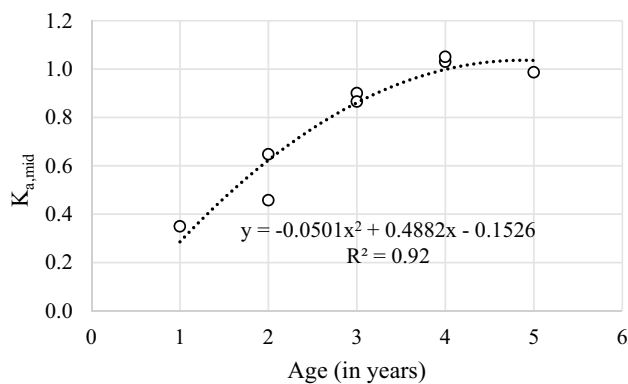
Figure 8 shows the actual daily crop coefficient ( $K_a$ ) as a function of the fraction of photosynthetically active radiation intercepted by the canopy (fPAR) estimated through lightbar measurements on 05 June 2019, 24 July 2019, and 19 June 2020. As fPAR increased,  $K_a$  increased linearly [ $K_a = 0.996 \times \text{fPAR} + 0.4936$ ] with a satisfactory  $R^2$  of 0.62.

### Discussion

Daily  $ET_a$  peaked in June through August for each age orchard and each year of the study, as shown in Fig. 5a–c. Other recent studies on crop water use of almond orchards in California, United States demonstrated the same temporal trend in daily  $ET_a$  (Sanden 2007; Sanden et al. 2012; Bellvert et al. 2018). Daily  $ET_a$  was relatively consistent in June through August with little or no precipitation and clear sky conditions. Precipitation and ephemeral clouds in the spring and fall months resulted in some sporadic  $ET_a$  estimates, which was also demonstrated by Sanden et al. (2012) for mature almond orchards in California.



**Fig. 6** Daily actual crop coefficients ( $K_a$ ) for young almond orchards in 2018 (a), 2019 (b), and 2020 (c)



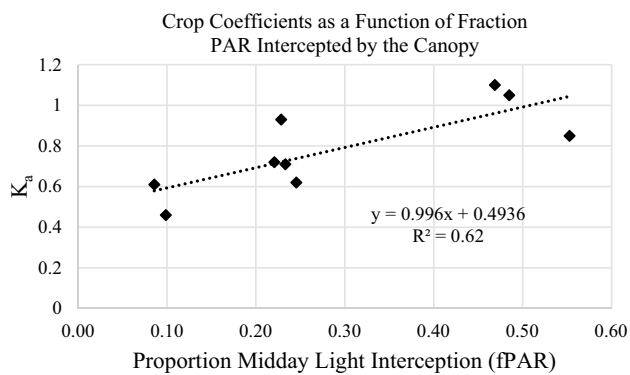
**Fig. 7** Mid-season actual crop coefficients,  $K_{a,mid}$  in young almond orchards of age 1 to 5 years near Corning, CA, United States

The grower’s irrigation scheduling resulted in a peak in  $ET_a$  after each irrigation event followed by a period of decreasing  $ET_a$  for several days, as also demonstrated by Bellvert et al. (2018) for irrigated almond orchards in

California. The grower’s reduction in irrigation during harvest activities in August and September reduced  $ET_a$  in the 3-, 4-, and 5-year-old orchards, which has been observed in other studies (Sanden et al. 2012; Stevens et al. 2012; Bellvert et al. 2018). Wildfire smoke from the LNU Lightning Complex Fires resulted in low net radiation in mid-August and September of 2020, resulting in reduced  $ET_a$  measurements.

The daily  $ET_a$  reached as high as  $9.20 \text{ mm day}^{-1}$  and  $9.31 \text{ mm day}^{-1}$  on June 30, 2020, in the 4- and 5-year-old almond orchards at 22% and 55% fPAR, respectively (on June 19, 2020), which is drastically higher than the daily transpiration of  $4 \text{ mm day}^{-1}$  for 50% ground cover (similar to fPAR) observed by Espadafor et al. (2015) in young almond trees. Transpiration will be lower than evapotranspiration because it does not consider the evaporation component, so comparing this study’s results to Espadafor et al. (2015) is not exactly an equivalent comparison but it is similar.

The  $ET_a$  estimates from this study were similar to those from Jarvis-Shean and Fulton (2018) in California, United



**Fig. 8**  $K_a$  as a function of the fraction of PAR intercepted by the canopy in young almond orchards of age 1 to 5 years near Corning, California, United States

States. This study's 1-year-old  $ET_a$  estimates of 61 and 67 mm in June and July were close to the Jarvis-Shean and Fulton (2018) estimates of 64 and 68 mm, respectively. This study's August and September 1-year-old  $ET_a$  estimates of 47 and 28 mm were considerably lower than the Jarvis-Shean and Fulton (2018) 1-year-old estimates of 61 and 45 mm, respectively. This study's 2-year-old  $ET_a$  estimates from P17 (orchard planted in 2017) were 105, 92, and 48 mm in August, September, and October, respectively, and from P18 (orchard planted in 2018) were 84, 50, and 25 mm in August, September, and October, respectively, compared to the Jarvis-Shean and Fulton (2018) estimates of 112, 82, and 49 mm in August, September, and October, respectively. This study's 3-year-old  $ET_a$  estimates were 198, 193, 129, 95, and 86 mm from P17 (orchard planted in 2017) in June, July, August, September, and October, respectively, and 175, 197, and 137 mm from P18 (orchard planted in 2018) in June, July, and August, respectively, compared to the Jarvis-Shean and Fulton (2018) estimates of 159, 171, 152, 112, and 67 mm in June, July, August, September, and October, respectively.

Evapotranspiration was the largest component in each of the soil water balances shown in Tables 3 through 5. The close estimates of  $ET_a$  determined by eddy covariance energy balance method and soil water balance methods (less than 20% absolute value error and often less than 10% absolute value error) validate the  $ET_a$  estimates determined in this study for determining crop water use and crop coefficients.

This study produced seasonal  $ET_a$  estimates for 3-, 4-, and 5-year-old almond orchards in 2020 only because not the whole season of data was determined for the 1- and 2-year-old orchards in 2018 and 2019. Seasonal  $ET_a$  estimates of drip-irrigated young almond trees from Fereres et al. (1982) of 262, 457, and 643 mm for 3-, 4-, and 5-year-old almond trees, respectively, were lower than this study's cumulative  $ET_a$  from full bloom until the end of harvest activities of

888, 1075, and 995 mm for 3-, 4-, and 5-year-old almond trees, respectively. Differences in tree density (188 trees per hectare in 1982 versus 348 trees per hectare in this study) and improved orchard management practices could explain the increased  $ET_a$  between 1982 and 2020.

The  $K_a$  shown in Fig. 6a–c increased with increasing age, indicating the need for different crop coefficients for each age of young almond orchards. Like the  $ET_a$  estimates,  $K_a$  also tended to be more consistent in the summer months, June through August, when  $ET_o$  was more consistent from day to day.  $K_a$  became erratic in the spring and fall months, primarily because the  $ET_o$  and  $ET_a$  were so small that any changes in one or the other resulted in considerable changes in  $K_a$ , which has also been observed by crop coefficients derived from micro-meteorological methods such as Sanden et al. (2012).  $K_a$  exhibited oscillations due to changes in water stress and evaporation from the soil surface. Evaporation from the soil surface and transpiration from the trees declined following each irrigation event, which has been seen by other studies on  $K_a$  in irrigated almond orchards (Bellvert et al. 2018). García-Tejero et al. (2015) observed that the crop coefficient ranged from 0.4 to 1.1 for 4-year-old almond trees in a lysimeter study, which is tighter than the 0.3 to 1.2 range in  $K_a$  observed before harvest in this study from the 4-year-old almond orchards in 2019 and 2020 in this study. Differences in the ranges may be the result of higher tree density compared to the García-Tejero et al. (2015) study where the trees were confined to the 3 m × 3 m × 1 m space of a lysimeter. The plant density (number of trees per hectare) was higher in this study (348 trees per hectare) than in other published studies on evapotranspiration and crop coefficients for almonds. Other studies on crop coefficients for almonds had plant densities ranging from 238 to 286 trees per hectare (Stevens et al. 2012; Espadafor et al. 2015; García-Tejero et al. 2015; Bellvert et al. 2018; López-López et al. 2018; Rallo et al. 2021).

The mid-season  $K_a$  for young almond orchards ages 1 to 3 years in this study (0.35, 0.55, and 0.88, respectively) were lower than in any of the reported mid-season crop coefficient values for mature almond orchards (Doorenbos and Pruitt 1977; Allen et al. 1998; Sanden 2007; Allen and Pereira 2009; Goldhamer and Girona 2012; Sanden et al. 2012; Stevens et al. 2012; García-Tejero et al. 2015; Bellvert et al. 2018). The mid-season  $K_a$  for almond orchards ages 4 and 5 years in this study (1.04 and 0.99, respectively) were within range of the mature almond orchards (0.9 to 1.3).

Mid-season crop coefficients for young almond orchards from Spain do not correspond with mid-season  $K_a$  from California (this study), possibly due to lower plant densities in Spain than in California almond orchards and differences in the irrigation method. For example, 238 trees per hectare in southeast Spain from 2017 to 2019 resulted in average mid-season crop coefficients,  $K_{c,mid}$ , of 0.30, 0.33, and 0.45



for ages 2, 3, and 4 years (Sánchez et al. 2021) compared to 0.55, 0.88, and 1.04 for ages 2, 3, and 4 years in this study. Lower mid-season crop coefficients in Spain compared to California could also be due to different soil water evaporation patterns in the drip-irrigated orchards (Espadafor et al. 2015; Sánchez et al. 2021), compared to micro-sprinkler irrigated orchards (this study). Drip irrigation usually has higher application efficiency than micro-sprinkler irrigation (Sandoval-Solis et al. 2013). Large evaporation losses can occur in micro-sprinkler irrigated almond orchards during and immediately after irrigations, influencing the net water balance and evapotranspiration (Koumanov et al. 1997).

The correlation between age and  $K_{a,mid}$  shown in Fig. 7 was excellent ( $R^2=0.92$ ) and showed that the  $K_{a,mid}$  peaked at age 4.9 years for the young almond orchards ages 1 to 5 years in this study. This relationship indicates that almond farmers need to adjust the crop coefficient as the almond orchards develop until at least the 4th year before using the mature almond orchard crop coefficient values.

$K_{a,mid}$  from this study were equivalent to 33, 52, 84, 98, and 93% of the average mature almond  $K_c$  (1.06) estimates from Sanden (2007) in June through August that were obtained from eddy covariance heat flux estimates of  $ET_c$  divided by the modified Penman  $ET_o$  data. By the 4th year,  $K_{a,mid}$  had approached 98% of mature almond  $K_c$ . The 5-year-old orchard (planted in 2016) had a lower  $K_{a,mid}$  than the  $K_{a,mid}$  of the 4-year-old orchard, which emphasizes that factors other than age, such as water stress and tree development, are important to  $K_{a,mid}$ . The difference in  $K_{a,mid}$  of the 4- and 5-year-old orchards may have been due to extreme water stress in the orchard planted in 2016 during August of 2019 during harvest activities (midday stem water potential as low as -3.1 MPa on August 21, 2019) which may have reduced shoot growth and tree development, carrying over to lower  $ET_a$  levels in 2020. Another explanation would be that the 5-year-old trees in 2020 were not irrigated enough to compensate for the year older trees than the 4-year-old trees and, as a result, the  $ET_a$  was lower in the 5-year-old trees than in the 4-year-old trees. Any possible effects on the  $K_{a,mid}$  versus age relationship from water stress or tree development were small, resulting in a clear plateau in  $K_{a,mid}$  after the 4th year as demonstrated by Fig. 7. The lower  $K_{a,mid}$  in the 4- and 5-year-old orchards compared to Sanden (2007) also may be due to the commercial grower's difficulty in controlling water stress during the harvest season. The Sanden (2007) study attempted to control water stress through neutron probe and stem water potential readings, which was not done in the present study since it was a purely grower managed commercial orchard.

Fraction of light intercepted by the canopy at midday (fPAR) had a good correlation with daily  $K_a$  ( $R^2=0.62$ ), which possibly could have been improved if water stress were controlled. Ayars et al. (2003) obtained a better

relationship ( $R^2=0.86$ ) between fraction of light intercepted by the canopy at midday by controlling water stress in a lysimeter study in peach (a *Prunus* plant like almond). The Doorenbos and Pruitt (1977) recommendation for a reduction in maximum  $K_c$  value (around 1.2 for mature almond) by 25–35% and by 10–15% for canopies with 20 and 50% ground cover, respectively, is equivalent to  $K_c$  of 1.02 to 1.08 for 50% ground cover and 0.78 to 0.90 for 20% ground cover, which are both higher compared to this study's observations of 0.99 and 0.69 for  $K_a$  at 50 and 20% midday light interception (similar to ground cover). The discrepancy might be due to the presence of water stress that resulted in lower  $K_a$  values in this study than  $K_c$  values from Doorenbos and Pruitt (1977) and uncertainty in the relationship between  $K_a$  and fPAR. By 55% fPAR in this study, the  $K_a$  of the developing almond orchard reached 98% of the average mature almond  $K_c$  (1.06) estimates from Sanden (2007) in June through August.

A limitation of this study is that the crop coefficients were not determined in a controlled environment that prevented water stress from occurring in the orchards. Actual crop coefficients,  $K_a$ , not standard crop coefficients,  $K_c$ , as described in Jensen and Allen (2016) and Allen et al. (1998) were determined in this study. The crop coefficients in this study were the ratio of the  $ET_a$  and  $ET_o$  of a commercial almond orchard and were affected by the grower's management practices. The farmer struggled to maintain adequate soil water content levels leading up to and during harvest activities when reduced irrigation was necessary to allow farm vehicles to enter the orchard and the farmer was concerned about over-irrigation. The farmer's irrigation scheduling resulted in sub-optimal, underirrigated conditions during the Nonpareil and Monterey harvest activities (August and September). Further research should investigate the crop water use of young almond orchards in an environment where water stress is controlled and prevented. This study provides insight on crop water use of one commercial almond farmer in the Sacramento Valley of California, United States.

## Conclusions

Actual evapotranspiration was measured using the eddy covariance energy balance method to estimate crop water use in young almond orchards aged 1-, 2-, 3-, 4-, and 5-years-old in the Sacramento Valley of California in the United States of America. Actual evapotranspiration increased as the orchards increased in age, indicating the need to adjust irrigation applied as orchards grow. The cumulative actual evapotranspiration from full bloom until the end of harvest activities were 888, 1075, and 995 mm in the 3-, 4-, and 5-year-old orchards in 2020, which was

higher than suggested by older research and research conducted for almond orchards outside of the Sacramento Valley of California. Actual crop coefficients were determined by calculating the ratio between actual evapotranspiration and reference evapotranspiration, resulting in an excellent correlation between the mid-season actual crop coefficient and age ( $R^2=0.92$ ). The mid-season actual crop coefficients were 0.35, 0.55, 0.88, 1.04, and 0.99 for 1-, 2-, 3-, 4-, and 5-year almond orchards. The relationship between the actual crop coefficient and the fraction of photosynthetically active radiation (an indicator of canopy size and development) was satisfactory ( $R^2=0.62$ ), suggesting that both age and development are important for determining crop coefficients. The results show that almond farmers should use age and development-specific crop coefficient values for irrigation scheduling until at least the 4th year when mature almond crop coefficients could be used. Reductions in daily actual evapotranspiration and daily actual crop coefficients aligned with decreases in midday stem water potential when irrigation was reduced during harvest activities in August and September and smoky sky conditions due to nearby wildfires. A major observation from this study is the importance of monitoring water stress in relation to changes in actual evapotranspiration for the interpretation of crop coefficients derived from evapotranspiration estimates. Knowledge of actual evapotranspiration and crop coefficients is valuable for water resources planning, surface water allocations, groundwater management compliance, and water trading. Further research should focus on determining crop water use by young almond orchards with different irrigation systems, varieties, soils, and management practices.

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## Declarations

**Conflict of interest** The authors declare no conflicts of interest or competing interests.

**Availability of data, code, and materials** Contact the corresponding author to request data, code, and material.

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