



Daily crop evapotranspiration and diurnal dynamics of the surface energy balance of a drip-irrigated blueberry (*Vaccinium corymbosum*) orchard

L. Octavio Lagos^{1,2} · Camilo Souto^{1,2} · Mario Lillo-Saavedra^{2,3} · Andrés Pérez¹ · Juan Hirzel⁴ · Mathias Kuschel-Otárola⁵ · Eduardo Holzapfel^{1,2} · Lucia Scaff^{2,6}

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Abstract

Accurate estimation of crop evapotranspiration (ET_c) considering global warming is a key aspect to optimize water application, yield and fruit quality for sustainable blueberry production. This study quantifies daily crop ET_c , diurnal dynamics of the surface energy balance (SEB) and the crop factor (CF) of a drip-irrigated blueberry (*Vaccinium corymbosum*) orchard field. CF is defined as the ratio of ET_c and reference ET. ET_c and the SEB were measured using an Eddy Covariance (EC) system every 30 min during four growing seasons. Results show maximum values of available energy, Net Radiation (R_n) minus soil heat flux (G), reached $18 \text{ MJ m}^{-2} \text{ d}^{-1}$, while that the sum of turbulent fluxes extended to $17 \text{ MJ m}^{-2} \text{ d}^{-1}$. Maximum values of latent heat (λE) normally occur on November–December from 10 to $11 \text{ MJ m}^{-2} \text{ d}^{-1}$. The correlation between R_n between crop rows and R_n above the crop canopy-soil surface was 0.73 during all growing seasons. G below the canopy represents 5% of R_n above the crop canopy-soil surface. During this study, ET_c reached up to 5.0 mm d^{-1} when ET_o was 7 mm d^{-1} . Maximum ET_c values occur during December. Weekly specific CF varied from 0.5 to 0.8 from October to March. CF showed no significant variation year to year suggesting that they could be used by farmers to better predict water demand and improve water use efficiency. To our knowledge, there are no previous studies at a field's scale documenting all components of the daily SEB and its diurnal dynamics over blueberry orchards.

Introduction

Blueberries are functional foods, and their consumption has increased because of their positive effects on people's well-being and health (Romo-Muñoz et al. 2019; Ortega-Farías et al. 2021). Blueberries are also being used as ingredients and additives to improve the quality and properties in foods and beverages. Due to all these combined consumptions, the trade and production of blueberries is expanding globally. Global production and trade have seen the most dramatic growth between 2010 and 2019, driven ever higher by mounting consumer demand. Global production more than doubled between 2010 and 2019, rising from 439,000 t to nearly 1.0 Mt (FAS-USDA 2021). During this time, the number of countries with reportable production expanded from 26 to at least 30, with 27 countries showing growth. In 2010, only 4 countries produced more than 10,000 tons: the United States (224,000 t), Canada (84,000 t), Chile (76,000 t), and France (11,000 t) (Protzman 2021).

Chile established blueberry as the first crop in the late 1980 s, however, the industry in the nation only began to

✉ L. Octavio Lagos
octaviolagos@udec.cl

¹ Departamento de Recursos Hídricos, Facultad de Ingeniería Agrícola, Universidad de Concepción, Avenida Vicente Mendez 595, Chillán, Chile

² Centro de Recursos Hídricos para la Agricultura y Minería (CRHIAM), Universidad de Concepción, Chillán 3812120, Chile

³ Departamento de Mecanización y Energía, Facultad de Ingeniería Agrícola, Universidad de Concepción, Avenida Vicente Mendez 595, Chillán, Chile

⁴ Instituto de Investigaciones Agropecuarias, INIA Quilamapu, Vicente Mendez Avenue 515, Chillán, Chile

⁵ Departamento de Suelos y Recursos Naturales, Facultad de Agronomía, Universidad de Concepción, Avenida Vicente Mendez 595, Chillán, Chile

⁶ Department of Geophysics, Faculty of Physical Sciences and Mathematics, Universidad de Concepción, Av. Esteban S Iturra, Concepción, Chile

grow up after 1997. From 2003 to 2007, the planted area increased from 2135 to 9940 *ha* and in 2019, the total area was 18,374 *ha* (Slot et al. 2019). Located in the southern hemisphere, Chile plays a pivotal role in extending the worldwide blueberry production season. Chilean production ships fruit to the northern hemisphere during the winter (November through March), when fresh fruit in those latitudes are not available (Beaudry et al. 1998).

According to the growth of the blueberry crop in Chile, some of the key limitations are the variation in the market exchange rate and the high harvest costs due the labor and investment in research and innovation (Retamales et al. 2014; Almonacid 2018). Farmers also recognize the challenge on managing the right amount of irrigation for optimizing total production and fruit quality. Water requirements and new irrigation strategies under global warming and climate change scenarios are currently key aspects for sustainable blueberry production.

Chilean farmers are concerned about the rate at which temperature is expected to increase during the second half of the 21st century (Beltrán 2018). The IPCC's moderate and severe climate change scenarios show that at the end of the century the temperature may rise up to 1–3 and 2–4°C in the northern and central parts of Chile, respectively (Parry et al. 2007; Beltrán 2018; Pabón-Caicedo et al. 2020). Moreover, economically valuable crops like blueberries are susceptible and vulnerable to climate change as 2–4°C increase of temperature may cause a decline in blueberry flower production (USDA 2000). Even though a warmer climate could decrease the number of frost days and thus benefit orchards crops (Parker et al. 2021), drought periods hurt global crop production (Lesk et al. 2016).

Chile has been facing a prolonged drought period of more than 10 years in recent decades (Garreaud et al. 2019). As such, water scarcity in Chile has become one of the outstanding problems, which are not only caused by climate variability and climate change but also by the increasing need of water resources due to the raise in on-going anthropogenic activities such as agriculture, mining, hydro power and others. Consequently, the government has declared water scarcity as an agriculture emergency in over more than 100 communities (Tempest 2019).

Blueberry production crucially relies on the amount of water applied and its distribution within the soil due to the superficial nature of its root system (Holzapfel et al. 2004). Farmers who adopt drip irrigation are experiencing quicker growth, larger and more uniform blueberries with increased yields. There are two reasons why drip irrigation is suitable for blueberry production: (a) blueberry plants have a fine and shallow root system, so the crop is vulnerable to water stress; and (b) blueberries grow best on well-drained soils (NETAFIM 2020). Usually, estimated water requirements are less than the irrigation requirements, and even more drip

irrigation requires less water than other means of irrigation like sprinkler (Breiman 2001). According to Holzapfel et al. (2004), the amount of water applied and its distribution within the soil has a significant effect on actual crop evapotranspiration (ET_c) and yield. An accurate estimation of ET_c is a crucial step-forward in developing strategies to optimize water application, yields and quality crops (Yunusa et al. 2000; Campos et al. 2010; Galleguillos et al. 2011).

There are several methods to measure and estimate actual ET_c that make a distinction between analytical approaches and empirical approaches (Rana and Katerji 2000). Among the analytical methods; lysimeters, Bowen ratio method (*BREB*), or Eddy Covariance (*EC*) systems are the most commonly used (Carrasco-Benavides et al. 2012). *EC* systems are often used in *ET* studies due to ease of set-up, the ability to provide a continuous direct sampling of the turbulent boundary layer and the possibility to associate measurements of the surface energy balance (*SEB*) components (Allen et al. 2011). The simplified *SEB* equation used here ($Rn - G = \lambda E + H$) is widely applied to estimate actual evapotranspiration as a residual of the *SEB* at a field and regional scale (i.e. Bastiaanssen et al. 1998; Allen et al. 2007; Cawse-Nicholson et al. 2021). The simplified *SEB* also provides information for other applications such as the analysis of ground and canopy surface temperatures in land surface models which are usually coupled in mesoscale and climate models (Sellers et al. 1996; Chen and Dudhia 2001).

Allen et al. (1998) established that under standard condition evapotranspiration is often calculated as the product of a crop-specific coefficient (K_c) and reference evapotranspiration (ET_o). Under non-standard conditions, estimating K_c is complicated, because the canopies are not always uniform and their shape and size depends on pruning management techniques (Marsal et al. 2013). Although K_c values documented by the FAO-56 (Pereira et al. 2021) are valid for optimum agronomic and water management conditions, these values depend on the environmental and management conditions under which they were obtained such as the density of seeding or planting, fertilizing, tillage, irrigation method and watering frequency (Farahani et al. 2007; Hunsaker et al. 2003).

At present, few studies were focused on elucidating the relationship between ET_o and actual ET_c . Storlie and Eck (1996) used a lysimeter to obtain a K_c value of 0.27 in a 4-year-old low canopy cover, “Bluecrop” highbush blueberries, in New Jersey (USA), planted 1 *m* apart within rows and 3 *m* between rows with manual watering. Hunt et al. (2008) calculated monthly K_c values at 2 sites for a 3-year study period, with a mean K_c value of 0.69 for lowbush blueberry using daily weighing lysimeter in Maine (USA). In New South Wales (Australia), Keen and Slavich (2012) developed an adjusted K_c curve for a 5-year-old “Star” highbush blueberries, planted 0.8 *m* apart within rows and 3 *m*

between rows, with a drip irrigation system. The estimated K_c values (non measured) were 0.4 for the semi-dormancy stage with partial leaf fall, 0.8 on the peak water demand period from start of ripening through to end of harvest and 0.6 for the post-harvest through the vegetative growth stage. In a work by Williamson et al. (2015), measurements from non weighing drainage lysimeters were used to evaluate the water use of Highbush Blueberry in north central Florida irrigated by microsprinklers. They showed that the K_c curve generated in a monthly scale for a 0.9 m in-row by 3 m between row plant spacing, starts from a minimal value of around 0.4, then values showed a slow increase until 0.8. This behavior depends on plant spacing and canopy coverage, as was described in Allen et al. (1998). After that, the K_c then falls slightly to 0.7. The final decrease of the K_c values depends mainly on the permanence of leaves in the plant and dormancy, weather, irrigation and fertilization. In this work, we use CF defined as the ratio of ET_c and reference evapotranspiration (ET_0) calculated following the procedure of the standardized method proposed by ASCE-EWRI (2005). When crop fully satisfies water demand, then CF equals K_c .

To our knowledge, there are no previous studies documenting all components of the daily surface energy balance and its diurnal dynamics over blueberry orchards. The partitioning of R_n into λE , H and G fluxes allows us to understand the thermodynamic equilibrium between turbulent transport processes in the atmosphere and laminar processes in the sub-surface (Bastiaanssen et al. 1998). This is particularly critical for ET modeling as well as for estimating ET from SEB models that use remote sensing techniques (UAV and Satellites platforms). The main objective of this study is to quantify daily crop ET_c , the diurnal dynamics of all components of the SEB and crop factor CF of a drip-irrigated blueberry orchard field.

Materials and methods

Study region

This study is performed in the South-Central valley of Chile, in the Ñuble region. This region has an annual mean precipitation of 1025 mm and the average high and low temperatures are 20.6 and 7.6°C, respectively (DGA 2004). Blueberry plantations in Ñuble stand out with 4023.6 ha and a growth of 17.3%, accounting for 21.9% of all blueberry crops in the country (Slot et al. 2019). Like other fruit trees such as cranberry, hazelnut, cherry, raspberry, and walnut, blueberries are also irrigated by micro-irrigation systems.

The annual pruning of this orchard normally occurs during the first half of May and it receives four applications of

chemical control during the year. The vegetative development of this crop takes its first growth flash in early October until the second half of December. The second growth flash starts from February until the first half of April. Flowering depends on the amount of chill hours that exist in the year, but usually starts during the first half of October and the fruit sets during the first half of November (100% fruit set). The fruit starts the stage of veraison from the second half of November until mid-December while the harvest starts from the second half of December until the first half of February.

Experimental site and instrumentation

ET_c and the SEB components were measured in the South-Central valley of Chile using an EC system for a six year old blueberry (*Vaccinium corymbosum*) field during four growing seasons (2011–2012, 2012–2013, 2013–2014 and 2014–2015). The study area is a field of 3.7 ha blueberry orchard belonging to the Ñuble Region, located at 36° 37.25' S, 71° 53.98' W, 125 m above sea level (a.s.l.) (Fig. 1).

The soil in the site is formed by volcanic ashes (Andisols) and its texture is silt loam, class 2, with a rooting depth of 1 m, however, the effective rooting depth was considered of 0.4 m. The site does not present a high heterogeneity in both horizontal and vertical (depth) axes with bulk density (ρ) ranging from 0.89 to 0.95 Mg m⁻³, soil water content at permanent wilting point (θ_{pwp}) and field capacity (θ_{FC}) ranging from 0.262 to 0.270 and from 0.481 to 0.494 m³ m⁻³, respectively. Thus, the total available soil water in the root zone (TAW) ranges from 108 to 116 mm.

In 2006 Legacy variety blueberries were planted in the study site with a standard spacing of 1 m in a row and 3 m between rows (3333.3 trees ha⁻¹) with a fraction of ground covered by vegetation of 0.55 - 0.61 during the growing seasons. Crop height was between 1.2 – 1.3 m above the soil's surface. The orchard under study is irrigated by a micro-irrigation system, with 2 emitters per plant and a discharge of 2.2 L h⁻¹. Irrigation starts the first week of October and lasts until the last week of April. Generally, during irrigation, one hour pulses are applied twice per day for six consecutive days, followed by one day of 3.5 h continuous application of water each week. There was not water stress during all four seasons.

An EC system was installed at the study area (Fig. 1) to measure both weather and energy related variables prior to evaluating the energy balance components at 30-min intervals. This EC system also included two radiometers (NR-Lite2, Kipp & Zonen, Delft, Netherlands) that allowed us to measure net radiation (R_n). While one of them was mounted at 1.2 m above the top of the crop canopy-soil surface, another one was installed in-between crop rows at 1.4 m above the soil surface. A combination of a 3D sonic anemometer (CSAT3, Campbell Scientific, Logan, UT, USA)

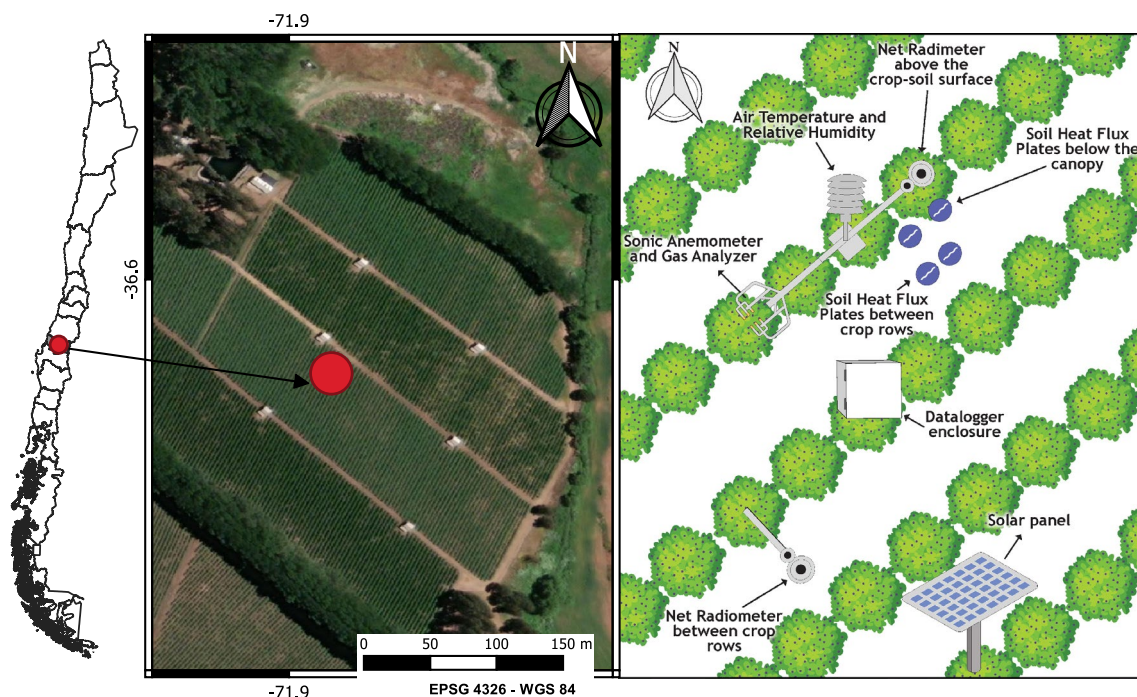


Fig. 1 The study site belonging to the Ñuble Region in the south-central valley of Chile. The Eddy Covariance station is represented with the red circle. (Source: Google Earth Image)

and a fine wire thermocouple (FW3, Campbell Scientific, Logan, UT, USA) recorded the sensible heat flux (H). The latent heat flux (λE) was measured through the combination of a sonic anemometer and a gas analyzer (EC150, Campbell Scientific, Logan, UT, USA), 1.2 m above the tree canopy, and the canopy height is between 1.5 and 1.9 m (during the 4 years of study), each instrument works at a frequency of 50 Hz. Four heat flux plates were placed in the field, (Hukseflux HFP01SC, Campbell Scientific, Logan, UT, USA), two of them were installed below the crop row and another two between rows monitored soil heat flux at 0.08 m depth. Soil temperature (T_{soil}) was measured by 4 averaging soil thermocouples for each soil heat flux plate (TCAV, Campbell Scientific, Logan, UT, USA), positioned at 0.02 and 0.06 m depths. Soil water content above the plates was measured by two soil water content reflectometers installed 0.025 m below the soil surface (CS616, Campbell Scientific, Logan, UT, USA). Air temperature (T_a) and relative humidity (RH) were recorded by a probe (HMP45C, Campbell Scientific, Logan, UT, USA). In addition, the soil water content was monitored using an analog data logger (Em5b, Decagon Devices, Pullman, WA, USA), 2 sensors (EC-5, Decagon Devices, Pullman, WA, USA) at 0.05 and 0.11 m depth, 3 sensors (10HS, Decagon Devices, Pullman, WA, USA) at 0.20, 0.30, and 0.40 m depth and 7 sensors (Watermark, Irrrometer, Riverside, CA, USA), 4 of them at 0.10, 0.25,

0.40 and 0.55 m depth in a row and 3 of them at 0.10, 0.25 and 0.40 m depth between rows. Canopy temperature (T_c) was monitored by an infrared radiometer (SI-400, Apogee Instruments, Logan, UT, USA), located at 2.0 m above the ground. The precipitation (Pp) was measured by a tipping-bucket rain gauge (Texas electronics TE525, Campbell Scientific, Logan, UT, USA). Data from the EC system and other sensors were stored in dataloggers models CR3000 and CR1000 (Campbell Scientific, Logan, UT, USA).

Available weather information

To compute reference evapotranspiration (ET_o) and the crop factor (CF) of blueberry, we gathered weather information from the nearest automatic weather station (AWS) every half an hour for the study period. The station was located at the University of Concepción experimental station (36°35'42.9" S, 72°4'47.8" W, 144 m a.s.l.) at 16 km from the study site. The atmospheric variables collected from this station encompasses solar radiation (R_s), RH , T_a , wind speed (u), and Pp (Fig. 2). Just as in the study site, this weather station is equipped with, a pyranometer (LI-200R, Licor, Lincoln, NE, USA), a probe (HMP45C, Campbell Scientific, Logan, UT, USA), an anemometer (3002, Campbell Scientific, Logan, UT, USA), a barometer (PTB101B, Campbell Scientific, Logan, UT, USA), and a rain gauge (TE525, Campbell Scientific, Logan, UT,

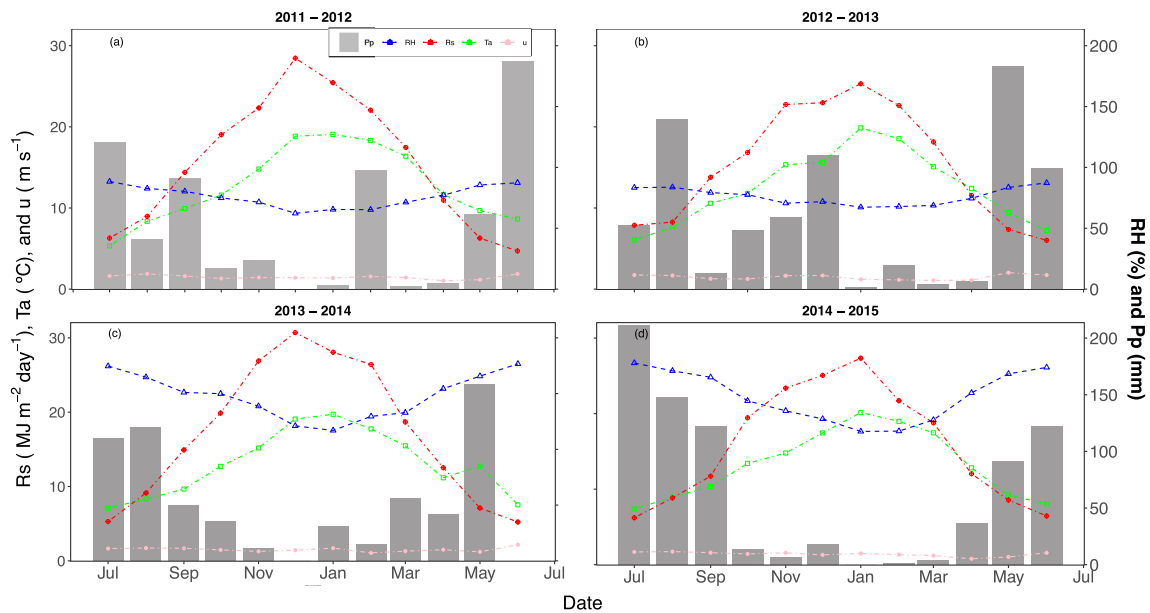


Fig. 2 Monthly weather observations is presented during each season. Grey bars show accumulated monthly precipitation (Pp), blue lines represent mean relative humidity (RH), red lines represent mean solar

radiation (Rs), green lines show mean air temperature (Ta) and light red lines show mean wind speed (u) (Color figure online)

USA) for R_s , RH , T_a , u , the barometric pressure (P) and PP , respectively. Finally, all this information was stored in a datalogger (CR1000, Campbell Scientific, Logan, UT, USA).

Data analysis

Data collection began in late October 2011 and lasted until July 2015. So the *SEB* component analysis was concentrated on four growing seasons spanning from June to July: (a) 2011–2012, (b) 2012–2013, (c) 2013–2014, and (d) 2014–2015 and from November to July in 2011–2012.

EC fluxes were corrected using the method proposed by Buck (1981), for high-frequency spectral losses by Moore (1986), the conversion of sonic temperature to air temperature by Schotanus et al. (1983), and a correction for density fluctuations by Webb et al. (1980); Buck (1981); Kaimal and Gaynor (1991); Leuning (2004). Almost every *EC* site shows an unclosed energy balance, which means that the available energy is found to be larger than the sum of the turbulent fluxes (Gebler et al. 2015; Foken 2008). In this study, the energy balance was corrected using the method proposed by Mauder et al. (2013, 2018). Mauder et al. (2013) use the energy balance residues, evaluated on a daily basis, and partition that energy between H and LE in a way that preserves the Bowen ratio (H/LE), according to:

$$H_{corr} = H/C \quad ; \quad LE_{corr} = LE/C \quad (1)$$

$$C = \frac{\sum_{i=1}^k (H + LE)}{\sum_{i=1}^k (Rn - G)} \quad (2)$$

where, “corr” indicate corrected fluxes and C a correction factor equal for both sensible and heat fluxes (adimensional). C represents the relative amount of energy balance closure evaluated on a daily basis and k is the number of valid observations of H and LE in each day, when $Rn > 20 \text{ W m}^{-2}$. In summary, this approach preserves the Bowen ratio of the daytime fluxes, while the nighttime data remain unchanged.

Understanding the interaction of land surface and vegetation cover with the surrounding atmosphere is crucial to watering the crops effectively and efficiently. In this aspect, this study examines the diurnal energy balance of the soil-canopy surface. As such, we investigated the dynamics of different components of surface energy balance: H , λE , and G fluxes with respect to the Rn , as reported in the literature Lima et al. (2011); Souza et al. (2012, 2018); Souto et al. (2019).

We aggregated hourly (or half-hourly) information to daily information to determine the daily λE as a summation of the 48 half-hourly values of λE (MJ m^{-2}). The energy needed to vaporize 1.0 mm depth of water from a 1.0 m^{-2} surface area is approximately 2.45 MJ m^{-2} . We divided the *SEB*-based λE by the coefficient $\lambda=2.45 \text{ MJ}$

$\text{kg d}^{-1} \text{m}^{-2}$ (equivalent to mm d^{-1}).

The amount of water applied and its distribution within the soil has an important effect on ET_c and yield (Holzapfel et al. 2004). According to Yunusa et al. (2000); Campos et al. (2010), and Galleguillos et al. (2011), an accurate estimation of actual ET_c is a crucial step in developing strategies to optimize water application, yields and quality. Due to the strong dependence of ET_c rate on weather (Hunt et al. 2008), a daily analysis was performed.

Footprint analysis

Footprint distribution reflects the relative contribution of different components in the upwind source area that influence a measured scalar EC flux as a function of observation height, vegetation properties, surface roughness, and other local environmental conditions. Since such information is related to the source strength of flux elements over a surface, footprint modeling might help us assess and understand the spatial extent of EC flux measurements (Schmid 1997; Yi 2008). The area of influence of the EC measurements was estimated by performing footprint analysis following the work of Kljun et al. (2015) for the four growing seasons. The Kljun et al. (2015) model is a simple two-dimensional parameterization for flux footprint prediction. Model inputs are roughness length (z_{om}), mean wind velocity (u) at the

measurement height, friction velocity (u^*), Obukhov length (L), and the standard deviation of lateral velocity fluctuations (σ_v), while the output of the model is a two-dimensional footprint function $f(x, y)$. To visualize the prevailing wind direction at the study site, an R package was used to generate the wind rose (R Core Team 2022).

Results and discussion

Footprint analysis

The footprint of the EC station is mainly including three blueberry orchards plots with the presence of two fields roads (Fig. 3). As shown in the left of Fig. 3, the footprint area during the 2012–2013 growing season contribute 90% of the measured fluxes coming from 53 to 84 m of distance. For the other growing seasons evaluated, the footprint was similar, with a minimal decrease in the southwest part of the field (approximately 15%). The shown footprint ensures that almost all of the fluxes comes from southwest direction in the study area (Fig. 3).

Energy balance closure

As an illustration, Fig. 4 portrays the relationship between the available energy ($R_n - G$) and the turbulent fluxes (H

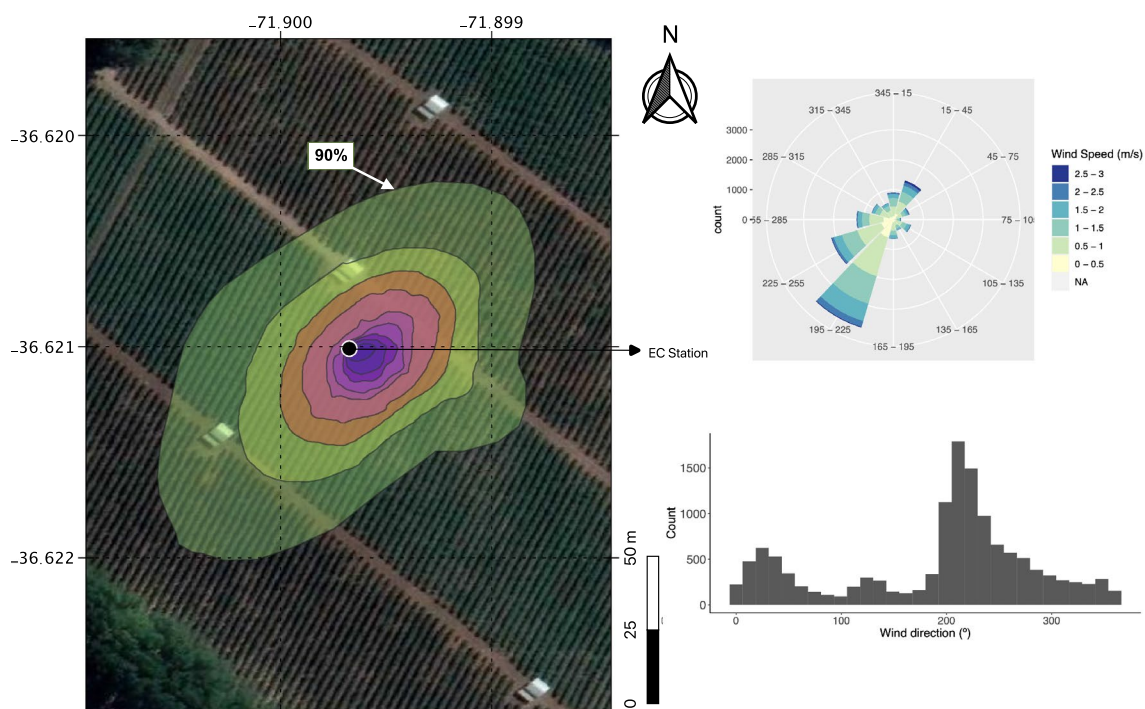


Fig. 3 Footprint analysis for 2012–2013 growing season. Left: footprint areas in the blueberry orchard; Top right: Wind rose of the EC system; Bottom right: portion of fluxes crossed over different wind direction. The flux recovery area is represented in Fig. with 90%

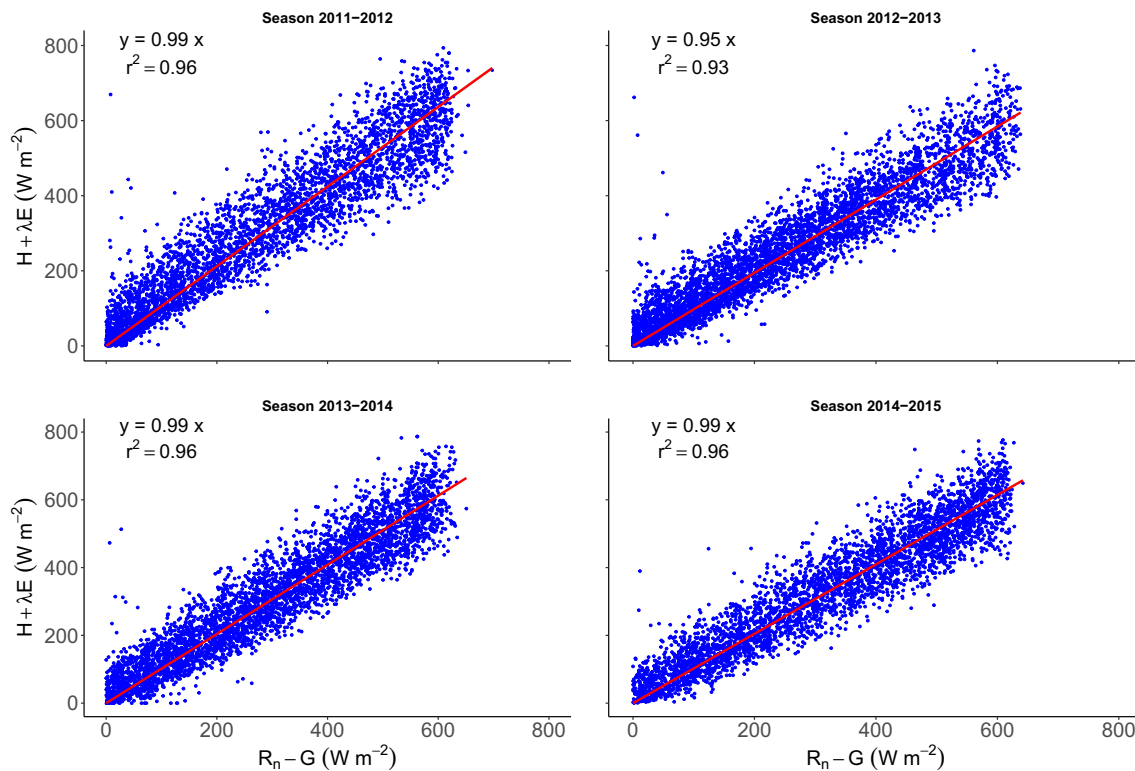


Fig. 4 Turbulent fluxes ($H + \lambda E$) with respect the available energy ($R_n - G$) for each growing season

+ λE) after corrections. As seen, the available energy and turbulent flux exhibit almost perfect linear relation corroborating the goodness of the EC measurements. All four seasons have similar regression slopes between 0.95 and 0.99 with coefficients of determination (r^2) between 0.93 to 0.96. Before corrections, the regression slope values were between 0.88 and 0.9, with the same determination coefficients found after the correction.

The relationship between observed R_n between rows (R_{ns}) and R_n over rows (R_{nc}) is included in Fig. 5. Regression slopes vary from 0.72 to 0.74 and the r^2 is 0.99 for all the growing seasons. As seen, R_{ns} is higher than R_{nc} as implied by the fact that in this case the vegetation cover albedo is higher than the bare soil albedo and hence the reflected energy over a vegetation cover is larger than the one over bare soil. The difference between R_{ns} and R_{nc} is

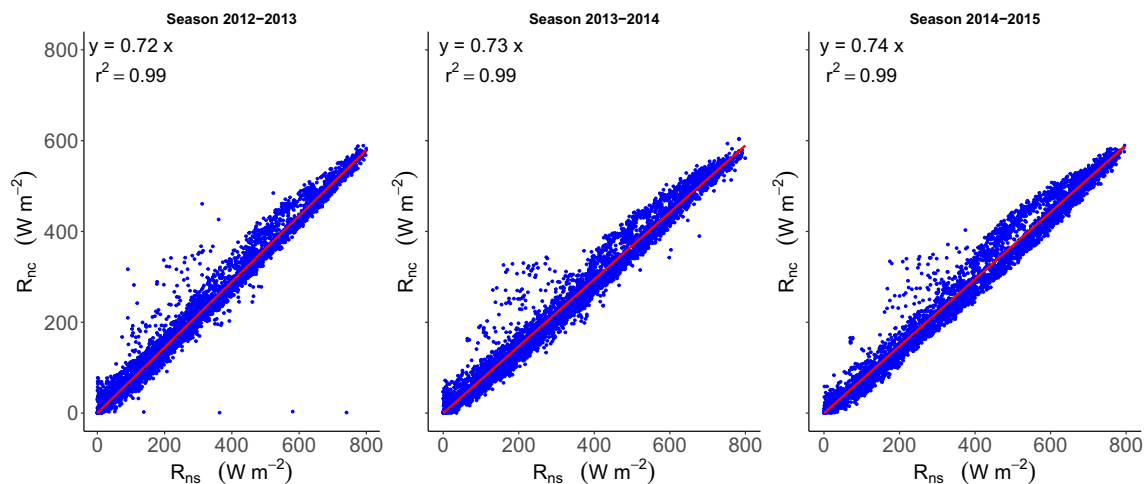


Fig. 5 Correlation for each growing season between the two measurements of R_n , between rows (R_{ns}) and over the canopy (R_{nc})

mainly controlled by the difference of soil and vegetation albedo but also for the presence of crop shadow and portions of wet soil. The silt loam soil texture in the field is dark, between rows the soil is partially wet and due to the orchard row orientation the bare soil is also partially shaded.

Diurnal dynamics of the surface energy balance components

Diurnal variation of these components for selected dates during four growing seasons during clear sky days and with clouds (e.g. Figure 6, on 12/16/2012). The analysis reflects hourly ensemble SEB fluxes during all growing seasons for the shown dates when there were no clouds. Cumulative daily G is slightly small and has insignificant contribution to λE .

The large magnitude of daytime H accounts for more than 50% of the daytime Rn and it turns negative at night (Fig. 6) indicating that release of heat in the night is inadequate to support this positive flux (Roberts et al. 2003). As seen, there is a significantly greater variation in H flux, among all SEB components while the range of G is very small. H flux measured by Eddy Covariance is more dominant throughout the growing season and peak in the afternoon (Chow et al.

2014). The diurnal trends seen in Fig. 6 for H , G and λE show similar behaviour in spring and summer. While Rn as mostly smooth Gaussian behavior, other components show a more rough dynamics, while G is stable throughout the period. It is also important to note that energy fluxes have higher values in the summer than in autumn. Besides, Rn is also consistently decreasing from late spring to early autumn in all four experimental seasons (Fig. 6). Such observation reveals lower energy available for H , λE and G (Retamal-Salgado et al. 2017). Table 1 lists the SEB model components with its key statistics, namely minimum, average, and maximum values in the observational period.

Seasonal dynamics of the surface energy balance components

As mentioned above, the relationship among SEB components expresses a distribution of the Rn in the other components (G , H and λE). The SEB components showed in Fig. 7 follow a similar pattern between them. They reach low values from May to August (lowest water demand months) and high values from November to February (highest water demand months). The Rn for all seasons (Fig. 7) reaches peak values between 16.5 and 17.5 MJ m⁻² d⁻¹ in summer

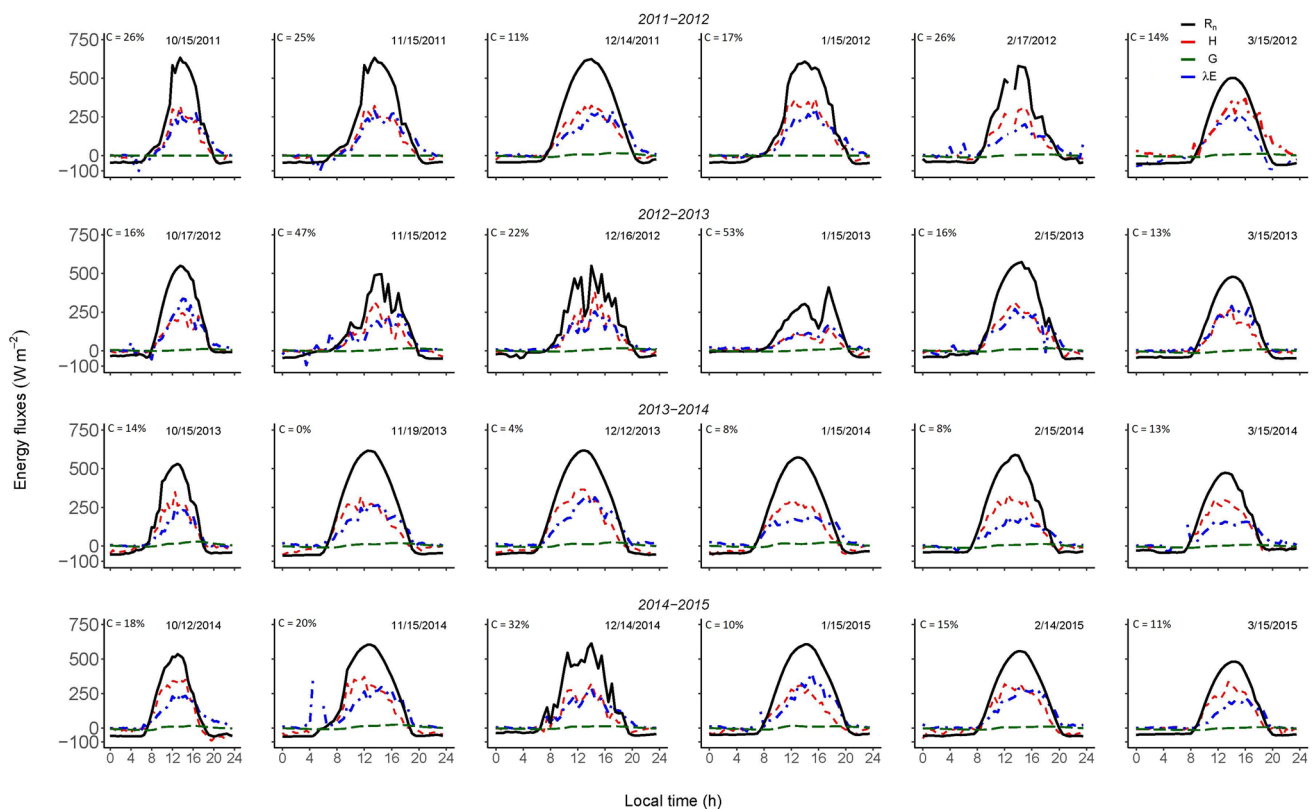


Fig. 6 Diurnal dynamics of surface energy fluxes in four growing seasons for shown dates entailing sensible heat flux (H , red), latent heat (λE , blue), net radiation (Rn , black), and ground heat flux (G , green) (Color figure online)

Table 1 Statistics of *SEB* components based on *EC* measurements over four growing seasons

SEB components	2011–2012			2012–2013			2013–2014			2014–2015		
	Min.	Avg.	Max.	Min.	Avg.	Max.	Min.	Avg.	Max.	Min.	Avg.	Max.
Sensible heat flux ($W\ m^{-2}$)	-177.6	67.5	519.7	-111.4	51.4	456.6	-139.1	84.1	468.3	-140.2	86.9	454.5
Net radiation ($W\ m^{-2}$)	-107.9	85.5	611.0	-73.3	73.7	679.1	-73.4	77.8	604.3	-68.2	100.5	663.1
Ground heat flux ($W\ m^{-2}$)	-33.5	2.7	37.6	-52.2	-2.1	71.2	-66.4	3.5	85.6	-61.3	-0.6	92.4
Latent heat flux ($W\ m^{-2}$)	-176.8	80.1	795.5	-156.8	67.0	677.3	-161.8	70.6	745.4	-163.2	83.1	766.5

Maximum (*Max*), Minimum (*Min*), and Average (*Avg*)

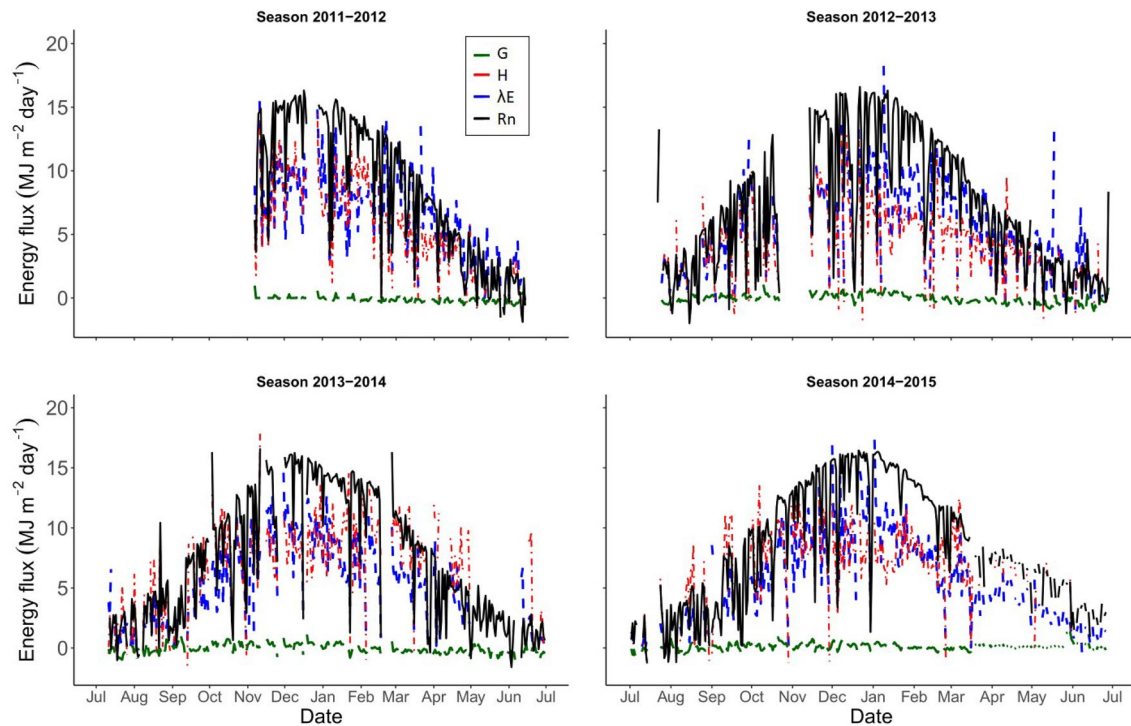


Fig. 7 *SEB* components for each growing season, for net radiation and soil heat flux data between rows (upper row) and over a row (lower row)

and below $5.5\ MJ\ m^{-2}\ d^{-1}$ in winter. The *H* flux (Fig. 7) reaches a peak value near to $12.5\ MJ\ m^{-2}\ d^{-1}$ in summer and below $4.0\ MJ\ m^{-2}\ d^{-1}$ in winter. Likewise, the λE flux reaches a peak value near to $14.0\ MJ\ m^{-2}\ d^{-1}$ in summer and around $3.0\ MJ\ m^{-2}\ d^{-1}$ in winter. The *Rn* between rows (R_{ns}) (Fig. 5) reaches a value near to $800\ Wm^{-2}$ in summer and a value near to $200\ Wm^{-2}$ in winter. Following the same- configuration of the sensors, the *G* flux between rows reaches a peak value near to $10\ Wm^{-2}$ in summer and $-10\ Wm^{-2}$ in winter. However, *Rn* over row (R_{nc}) for all seasons (Fig. 5) reaches a peak value of over $600\ W\ m^{-2}$ in summer and $200\ W\ m^{-2}$ in winter. *G* reaches a peak mean value of $20\ W\ m^{-2}$ in summer and $-10\ W\ m^{-2}$ in winter. A study conducted by Pardo et al. (2015) in Spain showed that the *SEB* components (*Rn*, *G*, *H* and λE) in non-irrigated annual

crops reach maximum average values about 422, 131, 173 and $103\ W\ m^{-2}$, respectively, highlighting the differences on *SEB* components with irrigated orchards. A recent study by Marino et al. (2021) highlights differences in *SEB* for pistachio orchards with variable soil salinity, finding values of *Rn* between 7 and $18\ MJ\ m^{-2}\ d^{-1}$ in the growing season, which is similar to *Rn* at the blueberry orchards field. However, maximum *H* flux is smaller for the pistachio orchards (between 0 and $5\ MJ\ m^{-2}\ d^{-1}$), while maximum λE is larger for pistachio orchards (about $200\ W\ m^{-2}$), than the blueberry ones. These differences in *SEB* could be explained by several factors, such as the atmospheric conditions (air temperature and humidity), plant physiological and physical characteristics and the variations on methods to measure and estimate *SEB* components.

Actual and reference evapotranspiration

The trends of ET_c and ET_o for four consecutive seasons considered are similar for all four growing seasons having maximum ET_c during the month of December and January with value between 5.5 to 6.5 mm d^{-1} (Fig. 8). Similar values of ET_c were found by Bryla (2011). However, the distribution of ET_c in the 2013–2014 growing season is wider than in the 2012–2013 and 2014–2015 growing seasons. In other words, the λE increases quickly in the beginning of the year in all growing seasons followed by a quicker drop during the 2012–2013 and 2014–2015 growing seasons than in the 2013–2014 one. In General, the orchard did not suffer any water stress during the four seasons.

Yearly dynamics of ET_o for four different years are shown in Fig. 8 and are quite similar to that of λE flux as portrayed in Fig. 7. As observed and as expected, the ET_o behaves in a similar manner, in the sense that peak value of over 7.5 mm d^{-1} occurs in the month of January for all periods. Further, note that the peak values of ET_o which occur in early January for the 4 years are within the range of 7.0–7.8 mm d^{-1} . But these ET_o values increased in the 2011–2012 and 2013–2014 growing seasons and then decreased again in the 2012–2013 and 2014–2015 growing seasons.

Crop and reference evapotranspiration ratio

Relying on the values of ET_c and ET_o , their ratio i.e. CF value as revealed in Fig. 9 also reaches a peak value of around 0.8 in November and December for all growing seasons. Similar values were showed by Hunt et al. (2008) when calculating monthly Kc values at 2 sites for 3-year study period, finding a mean Kc value of 0.69 in Maine, USA. While Keen and Slavich (2012) found Kc values between 0.4 to 0.8 for 5 year old highbush blueberries. However, the evolution of CF values exhibit more variability from year to year. As seen, the range of CF values was high in 2014 and 2015 as compared to the latter three seasons. It is also noted that the CF values try to remain stable from mid-December until March for all growing seasons (Fig. 9). Williamson et al. (2015) evaluated the water use of Highbush Blueberry in north central Florida, but irrigated using micro-sprinklers, and found similar values of CF .

The evolution of CF is normally affected by precipitation, so to calculate the weekly CF , we only considered dry days as presented in Fig. 9. There were no similar patterns of rainfall as well in terms of magnitude and timing among seasons. Note that there is more water for the 2012–2013 years than other two years despite the spikes during October–November, and February–March of 2013–2014.

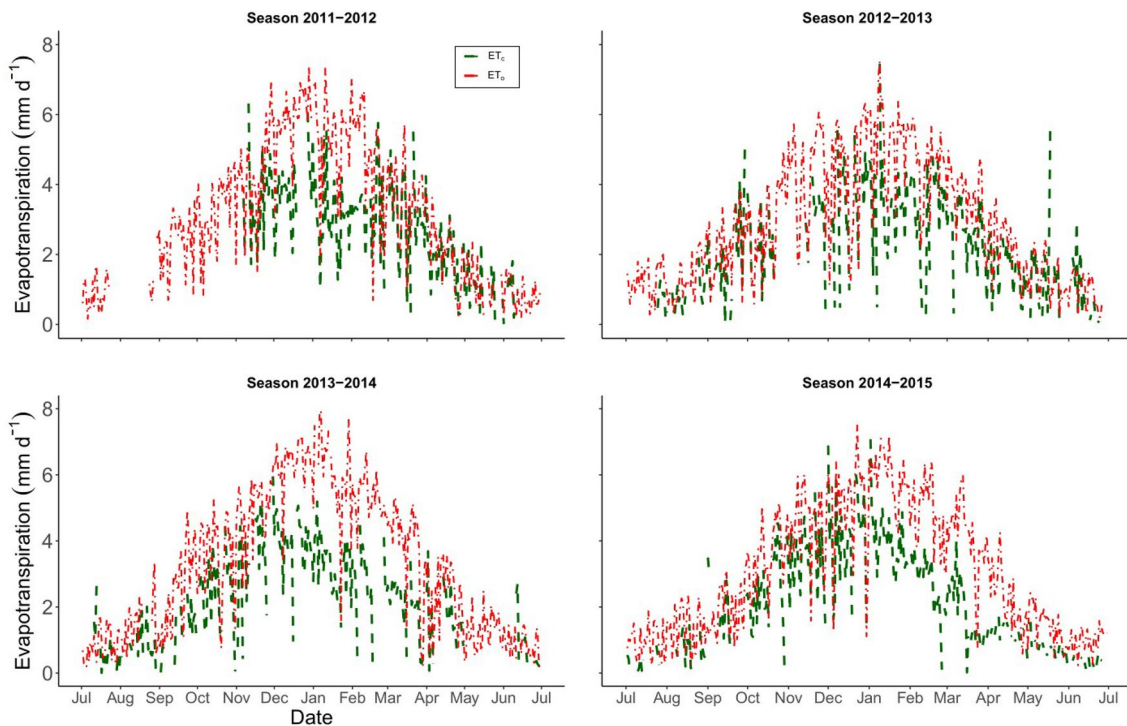


Fig. 8 Crop and reference evapotranspiration (ET_c and ET_o) evolution for each growing season

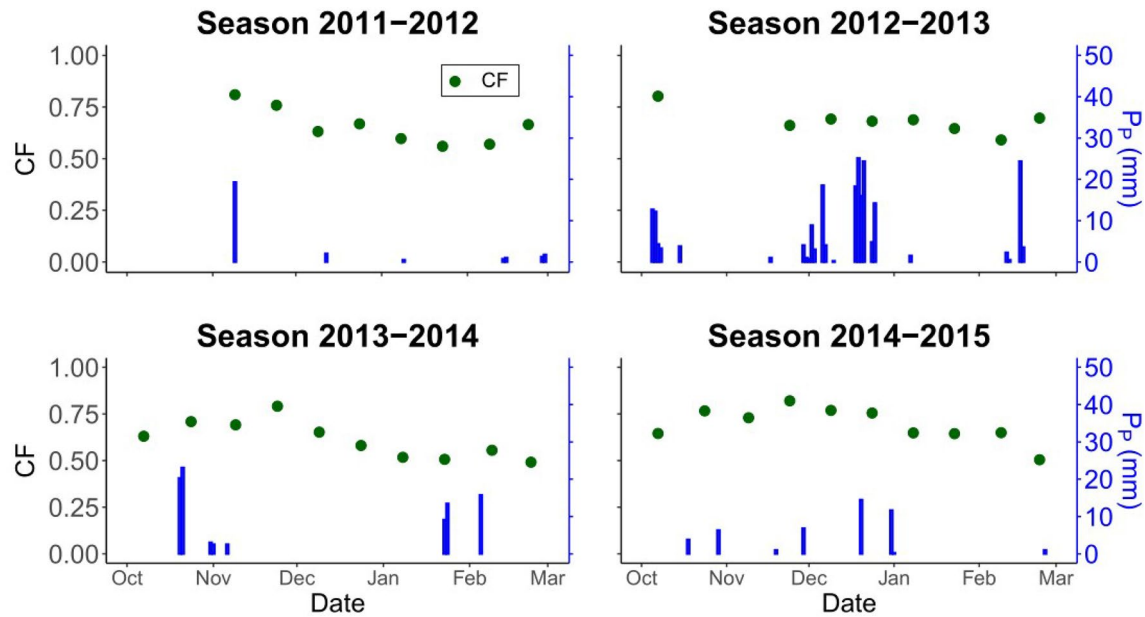


Fig. 9 Crop factor (CF) and effective precipitation (Pp) behavior for each growing season

Summary and conclusions

The study was carried out in a drip-irrigated, Legacy variety blueberry orchard, between the seasons of 2011 and 2015 in the central valley of Chile. To quantify daily ET_c and the main SEB components (R_n , λE , H and G fluxes) an EC system was installed in a typical commercial orchard. The analysis showed that maximum values of available energy ($R_n - G$) reach $18 \text{ MJ m}^{-2} \text{ d}^{-1}$, while that the turbulent fluxes ($\lambda E + H$) extent to $17 \text{ MJ m}^{-2} \text{ d}^{-1}$. Maximum values of λE normally occur on November–December ranging from 10 to $11 \text{ MJ m}^{-2} \text{ d}^{-1}$. The correlation between R_{ns} and R_{nc} was approximately 0.73 during all growing seasons. G fluxes beneath the canopy reach maximum values of $1 \text{ MJ m}^{-2} \text{ d}^{-1}$ during all seasons representing around 5% of R_{nc} . During this study, ET_c reached up to 5.0 mm d^{-1} when ET_o was around 7 mm d^{-1} . Maximum ET_c values occur normally during December. Weekly specific CF varied from 0.5 to 0.8 from October to March, with higher values found in late November and December during all growing seasons.

The CF values showed no significant variation year to year suggesting that they could be used by blueberry growers to better predict water demand and consequently improve the water use efficiency of drip-irrigated blueberries orchards. To our knowledge, there are no previous studies at a commercial field scale documenting all components of the daily surface energy balance and its diurnal dynamics over blueberry orchards. The CF can eventually be compared with caution against K_c from other studies. Further efforts to improve the estimation of CF could focus on a more accurate estimation of the EB closure.

Measuring the SEB in an actual field provides information of the diurnal dynamics of the whole orchard including the interaction between crops and the bared soil rows, plus the year-to-year weather variability. Therefore, the results of this work could be used for further applications in irrigation scheduling and planning.

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Author contributions O.L. designed the study, O.L., C.S., A.P., and M.KO. processed the dataset, C.S. prepared the figures. All authors wrote and reviewed the manuscript.

Declarations

Conflicts of interest The authors declare that they have no conflict of interest.

References

- Allen RG, Pereira LS, Raes D, Smith M et al (1998) Crop evapotranspiration-Guidelines for computing crop water requirements-FAO Irrigation and drainage paper 56. FAO, Rome 300(9):D05109

- Allen RG, Tasumi M, Trezza R (2007) Satellite-based energy balance for mapping evapotranspiration with internalized calibration (metric)-model. *J Irrigat Drainage Eng* 133:380–394. [https://doi.org/10.1061/\(ASCE\)0733-9437\(2007\)133:4\(380\)](https://doi.org/10.1061/(ASCE)0733-9437(2007)133:4(380))
- Allen RG, Pereira LS, Howell TA, Jensen ME (2011) Evapotranspiration information reporting: I. Factors governing measurement accuracy. *Agricult Water Manag* 98(6):899–920
- Almonacid F (2018) Southern Chile as a part of global value chains, 1985–2016: Blueberry production and the regional economy. *Ager* 2018(25):131–158. <https://doi.org/10.4422/ager.2018.08>
- ASCE-EWRI (2005) The ASCE Standardized Reference Evapotranspiration Equation. ASCE-EWRI Standardization of Reference Evapotranspiration Task Committee, Report. <http://www.kimberly.uidaho.edu/water/asceewri/>. Accessed 6 June 2023
- Bastiaanssen WGM, Meneti M, Feddes RA, Holtslag A (1998) A remote sensing surface energy balance algorithm for land (SEBAL). Formulation. *J Hydrol* 212–213:198–212
- Beaudry RM, Moggia CE, Retamales JB, Hancock JF (1998) Quality of 'ivanhoe' and 'bluecrop' blueberry fruit transported by air and sea from Chile to north America. *Hort Sci* 33(2):313–317
- Beltrán JA (2018) Climate change in Chile: climatic trends and farmer's perceptions. *Eu-topías: revista de interculturalidad, comunicación y estudios europeos* 1(16):5–23
- Breiman L (2001) Random Forests. *Mach Learn* 45:5–32
- Bryla DR (2011) Crop evapotranspiration and irrigation scheduling in blueberry. Evapotranspiration-From measurements to agricultural and environmental applications Intech, Rijeka, Croatia pp 167–186
- Buck AL (1981) New equations for computing vapor pressure and enhancement factor. *J Appl Meteorol* 20(12):1527–1532
- Campos I, Neale CMU, Calera A, Balbontín C, González-Piqueras J (2010) Assessing satellite-based basal crop coefficients for irrigated grapes (*Vitis vinifera* L.). *Agricult Water Manag* 98(1):45–54
- Carrasco-Benavides M, Ortega-Farías S, Lagos LO, Kleissl J, Morales L, Poblete-Echeverría C, Allen RG (2012) Crop coefficients and actual evapotranspiration of a drip-irrigated Merlot vineyard using multispectral satellite images. *Irrigat Sci* 30(6):485–497
- Cawse-Nicholson K, Anderson MC, Yang Y, Yang Y, Hook SJ, Fisher JB, Halverson G, Hulley GC, Hain C, Baldocchi DD, Brunsell NA, Desai AR, Griffis TJ, Novick KA (2021) Evaluation of a conus-wide ecostress disalexi evapotranspiration product. *IEEE J Selected Top Appl Earth Observat Remote Sens* 14:10117–10133. <https://doi.org/10.1109/JSTARS.2021.3111867>
- Chen F, Dudhia J (2001) Coupling an advanced land surface-hydrology model with the Penn State-NCAR MM5 modeling system. Part I: Model implementation and sensitivity. *Month Weather Rev* 129(4):569–585
- Chow WT, Volo TJ, Vivoni ER, Jenerette GD, Ruddell BL (2014) Seasonal dynamics of a suburban energy balance in phoenix, Arizona. *Int J Climatol* 34(15):3863–3880
- DGA (2004) Diagnóstico y clasificación de los cursos y cuerpos de agua según objetivo de calidad. Cuenca del río Itata Santiago, Chile
- Farahani HJ, Howell TA, Shuttleworth WJ, Bausch WC (2007) Evapotranspiration: progress in measurement and modeling in agriculture. *Trans Asabe* 50(5):1627–1638
- FAS-USDA (2021) Blueberries Around the Globe - Past, Present, and Future. https://www.fas.usda.gov/sites/default/files/2021-10/GlobalBlueberriesFinal_1.pdf. Accessed 6 June 2023
- Foken T (2008) The energy balance closure problem: an overview. *Ecol Applicat* 18(6):1351–1367
- Galleguillos M, Jacob F, Prévot L, Lagacherie P, Liang S (2011) Mapping daily evapotranspiration over a Mediterranean vineyard watershed. *Geosci Remote Sens Lett, IEEE* 8(1):168–172
- Garreaud RD, Boisier JP, Rondanelli R, Montecinos A, Sepúlveda H, Veloso-Águila D (2019) The central Chile mega drought (2010–2018): a climate dynamics perspective. *Int J Climatol*. <https://doi.org/10.1002/joc.6219>
- Gebler S, Franssen HH, Pütz T, Post H, Schmidt M, Vereecken H (2015) Actual evapotranspiration and precipitation measured by lysimeters: a comparison with eddy covariance and tipping bucket. *Hydrol Earth Syst Sci* 19(5):2145
- Holzappel EA, Hepp RF, Mariño MA (2004) Effect of irrigation on fruit production in blueberry. *Agricult Water Manag* 67(3):173–184
- Hunsaker DJ, Pinter PJ Jr, Barnes EM, Kimball BA (2003) Estimating cotton evapotranspiration crop coefficients with a multispectral vegetation index. *Irrigat Sci* 22(2):95–104
- Hunt JF, Honeycutt CW, Starr G, Yarborough D (2008) Evapotranspiration rates and crop coefficients for lowbush blueberry (*Vaccinium angustifolium*). *Int J Fruit Sci* 8(4):282–298
- Kaimal J, Gaynor J (1991) Another look at sonic thermometry. *Boundary-Layer Meteorol* 56(4):401–410
- Keen B, Slavich P (2012) Comparison of irrigation scheduling strategies for achieving water use efficiency in highbush blueberry. *New Zealand J Crop Horticultural Sci* 40(1):3–20
- Kljun N, Calanca P, Rotach M, Schmid HP (2015) A simple two-dimensional parameterisation for flux footprint prediction (ffp). *Geosci Model Develop* 8(11):3695
- Lesk C, Rowhani P, Ramankutty N (2016) Influence of extreme weather disasters on global crop production. *Nature* 529:84–87. <https://doi.org/10.1038/nature16467>
- Leuning R (2004) Measurements of trace gas fluxes in the atmosphere using eddy covariance: Wpl corrections revisited. *Handbook Micrometeorol*. Springer, pp 119–132
- Lima JRdS, Antonino ACD, Lira CABdO, Souza ESd, Silva IdFd (2011) Balanço de energia e evapotranspiração de feijão caupi sob condições de sequeiro. *Revista Ciência Agronômica* 42(1):65–74
- Marino G, Zaccaria D, Lagos LO, Souto C, Kent ER, Grattan SR, Shapiro K, Sanden BL, Snyder RL (2021) Effects of salinity and sodicity on the seasonal dynamics of actual evapotranspiration and surface energy balance components in mature micro-irrigated pistachio orchards. *Irrigat Sci* 39(1):23–43
- Marsal J, Girona J, Casadesus J, Lopez G, Stöckle CO (2013) Crop coefficient (K_c) for apple: comparison between measurements by a weighing lysimeter and prediction by CropSyst. *Irrigat Sci* 31(3):455–463
- Mauder M, Cuntz M, Drüe C, Graf A, Rebmann C, Schmid HP, Schmidt M, Steinbrecher R (2013) A strategy for quality and uncertainty assessment of long-term eddy-covariance measurements. *Agricult Forest Meteorol* 169:122–135
- Mauder M, Genzel S, Fu J, Kiese R, Soltani M, Steinbrecher R, Zeeman M, Banerjee T, De Roo F, Kunstmann H (2018) Evaluation of energy balance closure adjustment methods by independent evapotranspiration estimates from lysimeters and hydrological simulations. *Hydrol Process* 32(1):39–50
- Moore CJ (1986) Frequency response corrections for eddy correlation systems. *Boundary-Layer Meteorol* 37(1–2):17–35
- NETAFIM (2020) How to water blueberries - blueberry drip irrigation. <https://www.netafimusa.com/agriculture/solutions-for-your-crop/blueberries/>. Accessed 6 June 2023
- Ortega-Farías S, Espinoza-Meza S, López-Olivari R, Araya-Alman M, Carrasco-Benavides M (2021) Effects of different irrigation levels on plant water status, yield, fruit quality, and water productivity in a drip-irrigated blueberry orchard under mediterranean conditions. *Agricult Water Manag*. <https://doi.org/10.1016/j.agwat.2021.106805>

- Pabón-Caicedo JD, Arias PA, Carril AF, Espinoza JC, Borrel LF, Goubanova K, Lavado-Casimiro W, Masiokas M, Solman S, Villalba R (2020) Observed and projected hydroclimate changes in the andes. *Front Earth Sci* 8:1–29. <https://doi.org/10.3389/feart.2020.00061>
- Pardo N, Sánchez ML, Pérez IA, García MA (2015) Energy balance and partitioning over a rotating rapeseed crop. *Agricult Water Manag* 161:31–40
- Parker L, Pathak T, Ostoja S (2021) Climate change reduces frost exposure for high-value california orchard crops. *Sci Total Environ*. <https://doi.org/10.1016/j.scitotenv.2020.143971>
- Parry M, Parry ML, Canziani O, Palutikof J, Van der Linden P, Hanson C (2007) Climate change 2007-impacts, adaptation and vulnerability: Working group II contribution to the fourth assessment report of the IPCC, vol 4. Cambridge University Press
- Pereira L, Paredes P, López-Urrea R, Hunsaker D, Mota M, Shad ZM (2021) Standard single and basal crop coefficients for vegetable crops, an update of fao56 crop water requirements approach. *Agricult Water Manag* 243:106196
- Protzman E (2021) Foreign agricultural service blueberries around the globe - past, present, and future
- R Core Team (2022) R: A language and environment for statistical computing. available online: <https://www.r-project.org/>. (Accessed on Nov 2022)
- Rana G, Katerji N (2000) Measurement and estimation of actual evapotranspiration in the field under mediterranean climate: a review. *Eur J Agron* 13(2–3):125–153
- Retamal-Salgado J, Vásquez R, Fischer S, Hirzel J, Zapata N (2017) Decrease in artificial radiation with netting reduces stress and improves rabbit-eye blueberry (*Vaccinium virgatum aiton*) 'ochlockonee' productivity. *Chilean J Agricult Res* 77(3):226–233
- Retamales JB, Palma MJ, Morales YA, Lobos GA, Moggia CE, Mena CA (2014) Blueberry production in chile: current status and future developments. *Rev Bras Frutic, Jaboticabal-SP* 1:58. <https://doi.org/10.1590/0100-2945-446/13>
- Roberts SM, Oke T, Voogt J, Grimmond C, Lemonsu A (2003) Energy storage in a european city center. In: Fifth international conference on urban climate, vol 1(05.09), p 2003
- Romo-Muñoz R, Dote-Pardo J, Garrido-Henríquez H, Araneda-Flores J, Gil JM (2019) Blueberry consumption and healthy lifestyles in an emerging market. *Span J Agricult Res*. <https://doi.org/10.5424/sjar/2019174-14195>
- Schmid H (1997) Experimental design for flux measurements: matching scales of observations and fluxes. *Agricult Forest Meteorol* 87(2–3):179–200
- Schotanus P, Nieuwstadt F, De Bruin HAR (1983) Temperature measurement with a sonic anemometer and its application to heat and moisture fluxes. *Boundary-Layer Meteorol* 26(1):81–93
- Sellers PJ, Randall DA, Collatz GJ, Berry JA, Field CB, Dazlich DA, Zhang C, Collelo GD, Bounoua L (1996) A revised land surface parameterization (SiB2) for atmospheric GCMs. Part I: Model formulation. *J Clim* 9(4):676–705
- Slot SB, McGregor N, Peters N, Durinck A, Rijke MH (2019) Chile: Area devoted to blueberries in region of Ñuble increases by 17.3%. <https://www.freshplaza.com/article/9151073/chile-area-devoted-to-blueberries-in-region-of-nuble-increases-by-17-3/>
- Souto C, Lagos O, Holzapfel E, Maskey ML, Wunderlich L, Shapiro K, Marino G, Snyder R, Zaccaria D (2019) A modified surface energy balance to estimate crop transpiration and soil evaporation in micro-irrigated orchards. *Water* 11(9):1747
- Souza PJDOPd, Ribeiro A, Rocha EJPd, Farias JRB, Souza EBd (2012) Sazonalidade no balanço de energia em áreas de cultivo de soja na amazônia. *Bragantia* 71(4):548–557
- Souza PJDOPd, Rodrigues JC, Sousa AMLd, Souza EBd (2018) Diurnal energy balance in a mango orchard in the northeast of pará, brazil. *Revista Brasileira de Meteorologia* 33(3):537–546
- Storlie CA, Eck P (1996) Lysimeter-based crop coefficients for young highbush blueberries. *Hort Sci* 31(5):819–822
- Tempest O (2019) Chile's water crisis. <https://smartwatermagazine.com/news/smart-water-magazine/children-need-clean-water-clean-air-and-a-safe-climate>. Accessed 6 June 2023
- USDA (2000) Blueberries, pollinators, and pests with wvu. <https://www.climatehubs.usda.gov/hubs/northeast/project/blueberries-pollinators-and-pests-wvu>. Accessed 6 June 2023
- Webb EK, Pearman GI, Leuning R et al (1980) Correction of flux measurements for density effects due to heat and water vapour transfer. *Quarterly J Royal Meteorol Soc* 106(447):85–100
- Williamson JG, Mejia L, Ferguson B, Miller P, Haman DZ (2015) Seasonal water use of southern highbush blueberry plants in a subtropical climate. *Hort Technol* 25(2):185–191
- Yi C (2008) Momentum transfer within canopies. *J Appl Meteorol Climatol* 47(1):262–275
- Yunusa IAM, Walker RR, Loveys BR, Blackmore DH (2000) Determination of transpiration in irrigated grapevines: comparison of the heat-pulse technique with gravimetric and micrometeorological methods. *Irrigat Sci* 20(1):1–8

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