Parameterization of a Clumped Model to Directly Simulate Actual Evapotranspiration over a Superintensive Drip-Irrigated Olive Orchard

CAMILO RIVEROS-BURGOS AND SAMUEL ORTEGA-FARIAS

Research and Extension Center for Irrigation and Agroclimatology (CITRA) and Research Program on Adaptation of Agriculture to Climate Change (A2C2), University of Talca, Talca, Chile

RAFAEL LÓPEZ-OLIVARI

Instituto de Investigaciones Agropecuarias, INIA, Carillanca, Temuco, Chile

JOSÉ LUIS CHÁVEZ

Civil and Environmental Engineering Department, Colorado State University, Fort Collins, Colorado

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ABSTRACT

The aim of this research was to evaluate the clumped model for estimating latent heat flux (LE) and actual evapotranspiration (ET_a) over a non-water-stressed olive orchard. Additionally, submodels to compute the net radiation R_n , soil heat flux G , and canopy resistance r_s^c were also included. For this objective, a database was used from an experimental unit inside a commercial superintensive drip-irrigated olive orchard located in the Péncahue Valley, Maule Region, Chile ($35^{\circ}23'S$, $71^{\circ}44'W$; 96 m above sea level) during the 2009/10 and 2010/11 growing seasons. The evaluation was carried out using measurements of LE obtained from an eddy covariance (EC) system. In addition, estimated values of R_n , G , and r_s^c were compared with ground-truth measurements from a four-way net radiometer, soil heat flux plates with soil thermocouples, and a portable porometer, respectively. Results indicated that the clumped model underestimated LE and ET_a with errors of 11.0% and 3.0%, respectively. Values of the root-mean-square error (RMSE), mean bias error (MBE), and index of agreement d_r for LE were 35 W m^{-2} , -1.0 W m^{-2} , and 0.96, while those for ET_a were 0.48 mm day^{-1} , 0.04 mm day^{-1} , and 0.64, respectively. The submodels computed R_n and G with errors less than 6% and RMSE values less than 65 W m^{-2} , while the Jarvis-type model predicted r_s^c with $\text{RMSE} = 41 \text{ s m}^{-1}$ and $\text{MBE} = 7.0 \text{ s m}^{-1}$. Finally, a sensitivity analysis indicated that the ET_a estimated by the clumped model was significantly affected by variations of $\pm 30\%$ in the values of the LAI and the minimum stomatal resistance $r_{s\text{min}}$.

1. Introduction

The water availability for irrigation has been reduced in the recent years due to frequent drought and competition between agriculture, industrial, and urban areas (Molden et al. 2010; Calzadilla et al. 2010; Hoekstra et al. 2012). The Mediterranean oliviculture areas, such as Chile, have been significantly affected by the changes in precipitation at local scale (Meza et al. 2012). Water scarcity has become into the main limitation to maintain the olive oil production. Thus, the estimation of water requirements plays an important role in establishing irrigation managements of olive orchards under water

scarcity scenarios. The water consumption is estimated through the computation of the actual evapotranspiration (ET_a), which is a function of the reference evapotranspiration (ET_o) and crop coefficients K_c (Allen et al. 1998). The main limitation of this approach is the selection of the right value of K_c , which may be markedly influenced by tree vigor, the training system (expressed in LAI and fractional vegetation cover f_c values) and nonlinear interactions of the soil, the cultivar and the climate conditions (López-Olivari et al. 2016; Martínez-Cob and Facci 2010). Additionally, K_c values can be affected by the partitioning of net radiation R_n into latent (LE), sensible H , and soil G heat fluxes. For a drip-irrigated olive orchard, Testi et al. (2004) showed that there was more energy distributed to evapotranspiration

Corresponding author: Samuel Ortega-Farias, sortega@utalca.cl

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(LE) than to heating air (H) as the leaf area increased from 0.01 to $1.0 \text{ m}^2 \text{ m}^{-2}$. Additionally, Ortega-Farias et al. (2016) indicated that in a drip-irrigated olive orchard ($f_c = 0.31$ and $\text{LAI} = 1.32 \text{ m}^2 \text{ m}^{-2}$), the H produced at the soil surface between rows was the main component of the orchard energy balance that affected the partitioning of ET_a into transpiration T and soil evaporation E . Thus, the direct estimation of ET_a over heterogeneous (or discontinuous) canopies of such orchards is very complex because water requirements are significantly affected by the partitioning of energy balance over the soil surface and the tree canopy.

For discontinuous canopies, incomplete soil cover leads to a differentiation of LE from soil in two sources: 1) soil under the canopy and 2) the bare soil between rows. Source 1 generates high LE and low H because there is high water content in the soil surface from the wetted area below the drippers, while source 2 yields low LE and high H because the water content in the soil surface is low, even close to the wilting point. Under these conditions, several researchers have suggested using clumped models to directly estimate ET_a over discontinuous canopies such as fruit orchards and vineyards (Poblete-Echeverría and Ortega-Farias 2009; Were et al. 2008; Zhou et al. 2006). The effectiveness of estimating ET_a from discontinuous clumped canopies has been reported in the literature (Domingo et al. 1999; Poblete-Echeverría and Ortega-Farias 2009; Were et al. 2008) considering the modifications proposed by Brenner and Incoll (1997) to the sparse-crop model of Shuttleworth and Wallace (1985). These modifications generated the clumped model, an approach that uses a mixture between the Shuttleworth–Wallace model and the energy distribution proposed by Dolman (1993), who suggested weighing the partitioning by the fractional cover from the plant and bare soil. The clumped model considers three sources from where LE is transferred to the atmosphere: the canopy, the soil under canopy, and the soil between rows. Then, ET_a is obtained by the sum of Penman–Monteith equations that estimate LE from each source, weighed by their fractional covers and a set of coefficients that represent the combination of aerodynamic resistances (Poblete-Echeverría and Ortega-Farias 2009). Unlike the Shuttleworth–Wallace model, which assumes that vegetation is uniformly distributed over a surface, the clumped model takes into account the clumping of the vegetation. This consideration would explain the changes in the energy absorbed by the plant canopy and the substrate below it (Brenner and Incoll 1997). In summary, this model differentiates LE sources into vegetative and nonvegetative components.

The clumped model has been applied in several heterogeneous canopies with an RMSE for ET_a ranging from 0.13 to 1.85 mm day^{-1} . For discontinuous canopy ($f_c = 34\%$, LAI is between 1.71 and $3.4 \text{ m}^2 \text{ m}^{-2}$), Brenner

and Incoll (1997) indicated that the clumped model underestimated T with an error of 5% . For bush vegetation in Spain ($f_c = 17\%$, $\text{LAI} = 0.81 \text{ m}^2 \text{ m}^{-2}$), Were et al. (2008) found that the clumped model estimated ET_a with an RMSE of 0.13 mm day^{-1} . For a discontinuous vegetated stand (*Anthyllis cytisoides* L.) ($f_c = 40\%$, LAI between 0.66 and $1.44 \text{ m}^2 \text{ m}^{-2}$), Villagarcía et al. (2010) reported RMSE values ranging from 0.21 to 1.85 mm day^{-1} . For a furrow-irrigated vineyard ($f_c = 35\%$ and $\text{LAI} = 0.2 \text{ m}^2 \text{ m}^{-2}$) in the arid desert region of northwest China, Zhang et al. (2008) observed that the clumped model underestimated LE by approximately 1% with a MAE of 32 W m^{-2} . Finally, for a drip-irrigated Merlot vineyard ($f_c = 30\%$ and LAI between 0.6 and $1.25 \text{ m}^2 \text{ m}^{-2}$), Poblete-Echeverría and Ortega-Farias (2009) estimated the LE and ET_a with RMSE values of 33 W m^{-2} and 0.32 mm day^{-1} , respectively.

To our knowledge, there is little information about the evaluation of LE and ET_a over hedge-pruned olive orchards trained on a superintensive system. Thus, the objective of this research was to parameterize the clumped model for estimating LE and ET_a over a commercial superintensive drip-irrigated olive orchard (*Olea europaea* L. cv. *Arbequina*) under non-water-stress conditions. Additionally, this study includes a parameterization of submodels for estimating R_n , G , and r_s^c .

2. Materials and method

a. Study site

A superintensive drip-irrigated olive orchard (cv. *Arbequina*) located in the Péncahue Valley, Maule Region, Chile ($35^\circ 23' \text{S}$, $71^\circ 44' \text{W}$; 96 m above sea level) was used to evaluate the clumped model during the 2009/10 and 2010/11 growing seasons. The experimental unit presented a clay loam texture soil texture and was classified as the Quepo series (Vertisol; fine, Thermic Xeric Apiaquerts). The trees were trained on a hedgerow system with a row spacing of $5.0 \text{ m} \times 1.5 \text{ m}$ and irrigated using two drippers per tree at a 2.0 L h^{-1} flow rate.

b. Field measurements

1) PLANT AND SOIL MONITORING

For irrigation management, the midday stem water potential ψ_x was measured at solar noon using a pressure chamber (PMS 1000, PMS Instrument Co., Corvallis, OR) during the two growing seasons (from flowering to harvest). A shoot (two per tree, one tree per replicate) with five or six pairs of leaves was encased in a plastic bag and wrapped in aluminum foil at least 2 h before measurement (Gómez-del-Campo 2013; Pierantozzi et al. 2013; Tognetti et al. 2007). Moreover, soil water content Θ at the 0 – 60 -cm

TABLE 1. List of sensors used for micrometeorological and meteorological measurements.

Instrument	Variables	Model	Scan/ averaging rate	Installation height from the surface (m)
3D sonic anemometer	Sensible heat flux	CSAT3 (Campbell Sci. Inc., Logan, UT)	10 Hz/30 min	5.1
Fast response IRGA	Latent heat flux	LI-7500 (LI-COR, Lincoln, NE)	10 Hz/30 min	5.1
Net radiometer	Net radiation from soil surface	Q7.1REBS (Campbell Sci. Inc., Logan, UT)	10 s/30 min	0.5
Four-way net radiometer	Albedo, incoming and outgoing shortwave radiation and longwave radiation from the canopy	CNR1 (Kipp and Zonen Inc., Delft, Netherlands)	10 s/30 min	5.1
Soil heat flux plates	Soil heat flux	HFT-3 (Campbell Sci. Inc., Logan, UT)	10 s/30 min	−0.08
Soil thermocouples	Soil temperature	TCAV (Campbell Sci. Inc., Logan, UT)	10 s/30 min	−0.02 and −0.06
	Temperature and relative humidity of the air and canopy	HMP-35 (Campbell Sci. Inc., Logan, UT)		1.5 and 5.1
Automatic meteorological station	Wind speed and direction	Wind sentry 3001 (Young, Traverse City, MI)	10 s/30 min	5.1
	Solar radiation	LI-200X (LI-COR, Lincoln, NE)		5.1

depth was measured using a portable time domain reflectometry unit (TRASE, Soil Moisture Corp., Santa Barbara, CA) with 20 pairs of rods inserted within and between the wet bulbs. Additionally, stomatal resistance r_{st} was measured using a portable porometer (PMR-5, PP Systems, Amesbury, MA). Finally, the LAI was measured weekly using a plant canopy analyzer (LAI-2000, LI-COR, Lincoln, NE), which was calibrated defoliating six trees for the two periods, where the leaves of each tree were photographed, and then the total leaf area per tree was measured using a digital image analysis. The calibrated equation was $y = 0.293x + 0.658$ ($r^2 = 0.91$), where y corresponds to the measured LAI from the defoliated trees and x is the uncalibrated LAI from the LAI-2000 measurements.

2) SURFACE ENERGY BALANCE DATA

The sensor descriptions for measuring meteorological variables and orchard energy balance components recorded by dataloggers (CR1000–CR5000, Campbell Scientific Inc., Logan, UT) are indicated in Table 1. The fast response and open-path infrared gas analyzer and the three-dimensional sonic anemometer were installed with a lateral separation of approximately 0.1 m for the EC system. The raw data (10 Hz) was postprocessed using the EdiRe software (University of Edinburgh, United Kingdom), which included the corrections of coordinate rotation (Wilczak et al. 2001), sonic temperature (Schotanus et al. 1983), and density effect (Webb et al. 1980). Surface energy balance data with unusual instrumental behavior, power failure and rain events were not used to validate the model. Moreover,

Et_a was calculated as the sum of LE between 0800 and 2000 UTC, in order to take into account only the mixing boundary layer (strong turbulence). The quality control of data was done through the computation of the energy balance closure using the energy balance ratio (EBR) as described below (Wilson et al. 2002):

$$EBR = \frac{H_{ec} + LE_{ec}}{R_n - G_{avg}}, \quad (1)$$

where R_n is the net radiation ($W m^{-2}$), G_{avg} is the average soil heat flux ($W m^{-2}$), and H_{ec} and LE_{ec} are the sensible and latent heat fluxes ($W m^{-2}$) computed after raw data postprocessing, respectively. To reduce the uncertainty associated with errors in the LE measurements, those days that presented an EBR with acceptable closure according to literature ($0.8 < EBR < 1.2$) were used in the analysis, otherwise they were discarded (Twine et al. 2000; Wilson et al. 2002; Liu et al. 2011; Ortega-Farias and López-Olivari 2012). Furthermore, the values of LE_{ec} for the selected days were recalculated using the Bowen ratio β as follows (Twine et al. 2000; Martínez-Cob and Faci 2010):

$$LE_{BR} = \frac{R_n - G_{avg}}{1 + \beta}, \quad (2)$$

$$\beta = \frac{H_{ec}}{LE_{ec}}. \quad (3)$$

After applying the data quality control, 47 days were available to validate the clumped model.

c. Model description

The actual evapotranspiration (ET_a ; mm day^{-1}) of the superintensive drip-irrigated olive orchard was estimated using the following expression:

$$ET_a = \sum_{i=1}^N \left(\frac{1800 LE_{ci}}{\lambda \rho_w} \right), \quad (4)$$

where LE_{ci} is the latent heat flux estimated by the clumped model (W m^{-2}) at 30-min intervals, λ is the latent heat of vaporization (MJ kg^{-1}), ρ_w is the density of water (kg m^{-3}), N is the number of measurements during the day. The 1800 number is a time conversion of s (30 min)^{-1} .

The clumped model computes LE_c as the sum of olive transpiration T , evaporation from soil under the canopy E_s , and evaporation from soil between rows E_{bs} weighted by the f_c (Brenner and Incoll 1997):

$$LE_c = f_c (C^c PM^c + C^s PM^s) + (1 - f_c) (C^{bs} PM^{bs}), \quad (5)$$

where PM^c , PM^s , and PM^{bs} are Penman–Monteith type combination equations for estimating the canopy

transpiration, evaporation from soil under canopy, and bare soil between rows (all in W m^{-2}), respectively; C^c is the canopy resistance coefficient; C^s is the soil resistance coefficient under plant; and C^{bs} is the soil resistance coefficient between rows (all dimensionless). These coefficients were calculated by the following equations:

$$PM^c = \frac{\Delta A + \left(\frac{\rho C_p D - \Delta r_a^c A_s}{r_a^a + r_a^c} \right)}{\Delta + \gamma \left(1 + \frac{r_s^c}{r_a^a + r_a^c} \right)}, \quad (6)$$

$$PM^s = \frac{\Delta A + \left(\frac{\rho C_p D - \Delta r_a^s A_c}{r_a^a + r_a^s} \right)}{\Delta + \gamma \left(1 + \frac{r_s^s}{r_a^a + r_a^s} \right)}, \quad (7)$$

$$PM^{bs} = \frac{\Delta A + \left(\frac{\rho C_p D}{r_a^a + r_a^{bs}} \right)}{\Delta + \gamma \left(1 + \frac{r_s^{bs}}{r_a^a + r_a^{bs}} \right)}, \quad (8)$$

$$C^c = \frac{R_{bs} R_s (R_c + R_a)}{R_s R_c R_{bs} + (1 - f_c) (R_s R_c R_a) + f_c (R_{bs} R_s R_a) + f_c (R_{bs} R_c R_a)}, \quad (9)$$

$$C^s = \frac{R_{bs} R_c (R_s + R_a)}{R_s R_c R_{bs} + (1 - f_c) (R_s R_c R_a) + f_c (R_{bs} R_s R_a) + f_c (R_{bs} R_c R_a)}, \quad \text{and} \quad (10)$$

$$C^{bs} = \frac{R_s R_c (R_{bs} + R_a)}{R_s R_c R_{bs} + (1 - f_c) (R_s R_c R_a) + f_c (R_{bs} R_s R_a) + f_c (R_{bs} R_c R_a)}, \quad (11)$$

where A , A_s , and A_c (all in W m^{-2}) correspond to the total energy available from the olive orchard and soil under tree canopy and olive canopy, respectively; ρ is the air density (kg m^{-3}); Δ is the slope of the vapor pressure versus temperature curve ($\text{kPa } ^\circ\text{C}^{-1}$); γ is the psychrometric constant ($\text{kPa } ^\circ\text{C}^{-1}$); C_p is the specific heat capacity of the air at constant pressure ($\text{J kg}^{-1} \text{K}^{-1}$); D is the vapor pressure deficit of the air (kPa) at the reference height z_r ; r_a^c is the aerodynamic resistance (s m^{-1}) of the olive from the leaf surface to the mean surface flow height z_m ; r_a^a is the aerodynamic resistance (s m^{-1}) between z_m and z_r ; r_a^{bs} is the aerodynamic resistance (s m^{-1}) between the bare soil surface between rows at z_m ; r_s^a is the aerodynamic resistance (s m^{-1}) between the soil under olive canopy at z_m ; r_s^c is the canopy resistance (s m^{-1}); r_s^s is the soil surface resistance (s m^{-1}) under olive canopy; and r_s^{bs} is the soil surface resistance (s m^{-1})

between rows. The values of R_c , R_s , R_a , and R_{bs} are estimated as follows:

$$R_c = (\Delta + \gamma) r_a^c + \gamma r_s^c, \quad (12)$$

$$R_s = (\Delta + \gamma) r_a^s + \gamma r_s^s, \quad (13)$$

$$R_a = (\Delta + \gamma) r_a^a, \quad \text{and} \quad (14)$$

$$R_{bs} = (\Delta + \gamma) r_a^{bs} + \gamma r_s^{bs}. \quad (15)$$

d. Parameterization

1) AVAILABLE ENERGY USING METEOROLOGICAL DATA

The values of A , A_c , and A_s were computed using the following expressions:

$$A = R_{ne} - G_e, \quad (16)$$

$$A_c = R_{ne} - R_{ns}, \quad (17)$$

$$A_s = R_{ns} - G_e, \quad \text{and} \quad (18)$$

$$R_{ns} = R_{ne} e^{(-cLAI)}, \quad (19)$$

where R_{ne} is the estimated net radiation over the olive orchard (W m^{-2}), G_e is the estimated soil heat flux (W m^{-2}), R_{ns} is the net radiation absorbed by the soil under canopy (W m^{-2}), LAI is the leaf area index ($\text{m}^2 \text{m}^{-2}$), and C is the extinction coefficient of the canopy for net radiation (dimensionless). The R_{ne} was computed as follows (Chávez et al. 2005; Ezzahar et al. 2007):

$$R_{ne} = (1 - \alpha)R_{si} + \varepsilon_a \sigma T_a^4 - \varepsilon_s \sigma T_s^4, \quad (20)$$

$$T_s = \sqrt[4]{f_c T_c^4 + (1 - f_c) T_{soil}^4}, \quad \text{and} \quad (21)$$

$$\varepsilon_s = f_c \varepsilon_c + (1 - f_c) \varepsilon_{soil}, \quad (22)$$

where α is the surface albedo (dimensionless), R_{si} is the incoming shortwave radiation (W m^{-2}), ε_a is the atmospheric emissivity (dimensionless), σ is the Stefan–Boltzmann constant ($\text{W m}^{-2} \text{K}^{-4}$), ε_s is the emissivity of the surface (dimensionless), T_a is the air temperature (K), T_s is the surface temperature (K), T_{soil} is the soil temperature (K), and T_c is the canopy temperature (K). The T_{soil} was obtained from a soil thermocouple buried at 8-cm depth; meanwhile, T_c was derived from the inverted longwave radiation measured by a four-way net radiometer (CNR1, Kipp and Zonen, Delft, The Netherlands). Also, ε_c and ε_{soil} are the emissivity of the canopy and soil, respectively. Values of ε_a were computed from air temperature and vapor pressure as (Brutsaert 1982):

$$\varepsilon_a = \phi \sqrt[7]{\frac{e_w}{T_a}}, \quad (23)$$

where e_w is the air vapor pressure (kPa) and ϕ is the calibration coefficient (dimensionless). To estimate G_e , a regression analysis between R_n and G_{avg} was performed using an independent dataset (50 days). In this case, G was estimated as follows (coefficient of determination $r^2 = 0.78$):

$$G_e = -24.7 + 0.3025 R_{ne}. \quad (24)$$

2) AERODYNAMIC RESISTANCES

Using the Shuttleworth and Gurney (1990) approach, values of aerodynamic resistance were estimated by the following expressions:

$$r_a^c = \frac{r_b}{LAI}, \quad (25)$$

$$r_b = \left(\frac{\eta}{a}\right) \left(\frac{w}{u_h}\right)^{0.5} (1 - e^{-n/2})^{-1}, \quad (26)$$

$$u_h = \left(\frac{u^*}{k}\right) \ln\left(\frac{h-d}{z_o}\right), \quad (27)$$

$$u^* = \frac{ku_r}{\ln\left(\frac{z_r-d}{z_o}\right)}, \quad (28)$$

$$z_o = z'_o + 0.3h(c_d LAI)^{0.5}, \quad \text{and} \quad (29)$$

$$d = 1.1h \ln[1 + (c_d LAI)^{0.25}], \quad (30)$$

where r_b is the mean boundary layer resistance of leaf per unit surface area of vegetation (s m^{-1}), η is the attenuation coefficient for wind speed (dimensionless), n is the eddy diffusivity decay coefficient (dimensionless), w is the average leaf width (m), a is a constant (dimensionless), u_h is the wind speed (m s^{-1}) at the top of the canopy average height, d is the displacement height (m), h is the height of the olive canopy (m), k is the von Kármán's constant (dimensionless), z_o is the roughness length (m), u^* is the friction velocity (m s^{-1}), u_r is the wind speed at z_r (m s^{-1}), c_d is the drag coefficient (dimensionless), and z'_o is the roughness length of the bare soil (m).

The values of r_a^a and r_a^s were estimated by the following expressions:

$$r_a^a = \left(\frac{1}{ku^*}\right) \ln\left(\frac{z_r-d}{h-d}\right) + \left(\frac{h}{nK_h}\right) \times \left\{ \exp\left[n\left(1 - \frac{Z_o + d_p}{h}\right)\right] - 1 \right\}, \quad (31)$$

$$r_a^s = \left(\frac{he^n}{nK_h}\right) \left\{ \exp\left(-\frac{nz'_o}{h}\right) - \exp\left[-\frac{n(Z_o + d_p)}{h}\right] \right\}, \quad \text{and} \quad (32)$$

$$K_h = ku^*(h-d), \quad (33)$$

where d_p is the zero-plane displacement height (m) (taken as $0.63h$), Z_o is the zero roughness length of the surface (m) (taken as $0.13h$), and K_h is the diffusivity at the top of the canopy ($\text{m}^2 \text{s}^{-1}$). The values of aerodynamic resistance r_a^{bs} between the bare soil surface and z_m were calculated assuming a linear variation between

r_a^b and r_a^s with f_c changing from 0 to 1 (Brenner and Incoll 1997; Villagarcía et al. 2007):

$$r_a^{bs} = f_c r_a^s + (1 - f_c) r_a^b, \quad (34)$$

$$r_a^b = \frac{\ln\left(\frac{z_m}{z_o'}\right)^2}{k^2 u_m}, \quad (35)$$

where r_a^b is the aerodynamic resistance (m s^{-1}) of bare soil completely unaffected by vegetation and u_m is the wind speed (m s^{-1}) at z_m .

3) CANOPY RESISTANCE

The canopy resistance r_s^c was estimated considering the Jarvis approach, according the equations used by Zhao et al. (2015):

$$r_s^c = \frac{r_{\text{stmin}}}{\text{LAI}} \frac{F_1}{F_2 F_3 F_4}, \quad (36)$$

where r_{stmin} is the minimal stomatal resistance (m s^{-1}); meanwhile F_1 , F_2 , F_3 , and F_4 (all dimensionless) indicate the effect of the photosynthetically active radiation, vapor pressure deficit of the atmosphere, air temperature, and soil moisture stress, respectively. Values of F_1 , F_2 , F_3 , and F_4 were estimated as follows (Noilhan and Planton 1989):

$$F_1 = \frac{1 + f}{f + \left(\frac{r_{\text{stmin}}}{r_{\text{stmax}}}\right)}, \quad (37)$$

$$f = \frac{0.55 R_{\text{si}}}{R_{\text{sl}}} \frac{2}{\text{LAI}}, \quad (38)$$

$$F_2 = 1 - 0.0025 D, \quad (39)$$

$$F_3 = 1 - 0.0016(298 - T_a)^2, \quad \text{and} \quad (40)$$

$$F_4 = \frac{\theta_i - \theta_{\text{MIN}}}{\theta_{\text{MAX}} - \theta_{\text{MIN}}}, \quad (41)$$

where r_{stmax} is the maximum stomatal resistance (m s^{-1}), R_{sl} corresponds to the threshold radiation (W m^{-2}) value above the stomata openness, and T_a is the air temperature (K). Values of θ_i , θ_{MAX} , and θ_{MIN} are actual, maximum, and minimum soil water contents ($\text{m}^3 \text{m}^{-3}$), respectively.

The observed values of r_s^c were computed according to Lafleur and Rouse (1990):

$$r_s^c = \frac{r_{\text{st}}}{\text{LAI}}, \quad (42)$$

For the clumped model, constant values used in this study are indicated in the Table 2.

e. Model performance

The performance of the clumped model was evaluated using the ratio of observed to estimated values r_{oe} , the root-mean-square error (RMSE), mean bias error (MBE), and index of agreement d_r . These statistical parameters are described as follows:

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^N (E_i - O_i)^2}{N}}, \quad (43)$$

$$\text{MBE} = \frac{1}{N} \sum_{i=1}^N (E_i - O_i), \quad \text{and} \quad (44)$$

$$d_r = 1 - \frac{\sum_{i=1}^N (E_i - O_i)^2}{\sum_{i=1}^N (|E_i - \bar{O}| + |O_i - \bar{O}|)^2}, \quad (45)$$

where N is the total number of observations; E_i and O_i are the estimated and observed values, respectively; and $\bar{O}$ is the mean of the observed values. Finally, a sensitivity analysis of the resistances (r_s^c and r_s^{bs}), LAI and constant variables (C , d , d_p , n , z_o , z_o' , and Z_o , r_{stmin} , and r_{stmax}) was conducted to assess their effects on the performance of the clumped model for estimating ET_a . To do this, the percent deviation of the mean ET_a was calculated when the LAI value, constant variables and resistances individually varied by $\pm 30\%$.

3. Results and discussion

The climatic conditions over the olive orchard were hot and dry during the two growing seasons. Table 3 indicates that mean values of T_a were between 17.7° and 21.1°C while those of D ranged between 1.0 and 4.0 kPa . Furthermore, the daily maximum R_n ranged between 667 and 764 W m^{-2} for both seasons. In the case of u , the average was approximately 1.5 m s^{-1} , with a maximum value of 4.7 m s^{-1} .

For the 2009/10 growing season, the average θ at 20- and 60-cm depth under the canopy were 0.09 and $0.23 \text{ m}^3 \text{m}^{-3}$, while those for the 2010/11 growing season were 0.11 and $0.18 \text{ m}^3 \text{m}^{-3}$, respectively. Meanwhile, the θ at 20-cm depth between rows for both growing seasons ranged 0.14 – $0.11 \text{ m}^3 \text{m}^{-3}$, respectively. Under these soil moisture conditions, ψ_x ranged between -1.43 and -1.96 MPa indicating that the olive trees were under null to mild water stress (Ahumada-Orellana et al. 2017).

TABLE 2. List of constants used in the clumped model.

Symbol	Name	Value	Units	Source
ρ_w	Density of water	1000	kg m^{-3}	Monteith and Unsworth (2014)
C_p	Specific heat capacity of the air at constant pressure	1013	$\text{J kg}^{-1} \text{K}^{-1}$	Monteith and Unsworth (2014)
σ	Stefan–Boltzmann constant	5.67×10^{-8}	$\text{W m}^{-2} \text{K}^{-4}$	Monteith and Unsworth (2014)
α	Surface albedo	0.17	Dimensionless	López-Olivari et al. (2015)
ε_c	Emissivity of the canopy	0.98	Dimensionless	Berni et al. (2009)
$\varepsilon_{\text{soil}}$	Emissivity of the soil	0.95	Dimensionless	Long and Singh (2012)
ϕ	Calibration coefficient of Brusaert's equation	1.75	Dimensionless	López-Olivari et al. (2015)
θ_{MIN}	Minimum soil water content	26.5	$\text{m}^3 \text{m}^{-3}$	Measured
θ_{MAX}	Maximum soil water content	15.9	$\text{m}^3 \text{m}^{-3}$	Measured
R_{sl}	Threshold radiation value above the stomata openness	30	W m^{-2}	Noilhan and Planton (1989)
r_{stmin}	Minimum stomatal conductance	181	s m^{-1}	Measured
r_{stmax}	Maximum stomatal conductance	283	s m^{-1}	Measured
n	Eddy diffusivity decay coefficient	2.5	Dimensionless	Shuttleworth and Wallace (1985)
η	Attenuation coefficient for wind speed	2.5	Dimensionless	Choudhury and Monteith (1988)
h	Height of the canopy	3.2	m	Measured
f_c	Fractional vegetative cover	0.3	Dimensionless	Measured
k	Von Kármán's constant	0.41	Dimensionless	Shuttleworth and Wallace (1985)
c_d	Drag coefficient	0.07	Dimensionless	Shuttleworth and Gurney (1990)
C	Extinction coefficient	0.68	Dimensionless	Ortega-Farias and López-Olivari (2012)
r_s^s	Resistance of the soil under the canopy	100	s m^{-1}	Brenner and Incoll (1997)
r_s^{bs}	Resistance of the bare soil surface	2000	s m^{-1}	Shuttleworth and Wallace (1985)
z_m	Mean surface flow height	2.43	m	Brenner and Incoll (1997)
w	Mean width of the leaf	0.015	m	Measured
z_r	Reference height	5.7	m	Measured
z_o'	Roughness length of bare soil	0.01	m	Sene (1994)
d_p	Zero-plane displacement	2.14	m	Shuttleworth and Wallace (1985)
d	Displacement height	1.5	m	Brenner and Incoll (1997)
z_o	Roughness length	0.3	m	Brenner and Incoll (1997)
Z_o	Zero roughness length	0.42	m	Shuttleworth and Wallace (1985)
a	Constant for estimate r_b	0.01	Dimensionless	Choudhury and Monteith (1988)

Additionally, the average values of f_c , LAI, and r_{st} were between 29% and 30%, between 1.16 and 1.65 $\text{m}^2 \text{m}^{-2}$, and between 181 and 283 s m^{-1} , respectively.

The obtained ratio of turbulent fluxes ($H_{\text{ec}} + \text{LE}_{\text{ec}}$) to available energy ($R_n - G$) was different from one ($\text{EBR} = 0.87$) indicating that the EC measurements presented a lack of energy closure equal to 13% (Fig. 1). For a young drip-irrigated orchard (f_c = between 1% and 25% and LAI = between 0.1 and 1.0 $\text{m}^2 \text{m}^{-2}$), Testi et al. (2004) reported an energy closure ranging between 85% and 95%, while for a flood-irrigated olive orchard, Williams et al. (2004) found a lack of energy closure of 26%. Ezzahar et al. (2007) reached an energy closure of 95% over a flood-irrigated olive orchard (f_c = 55%). Er-Raki et al. (2008) showed a lack of energy balance closure between 8% and 10% over a flood-irrigated olive orchard (f_c = between 15% and 20% and LAI = 3.0 $\text{m}^2 \text{m}^{-2}$). Cammalleri et al. (2013) obtained an energy closure between 90% and 92% in a drip-irrigated olive orchard (f_c = 35% and LAI between 1.1 and 2.4 $\text{m}^2 \text{m}^{-2}$). Finally, Martínez-Cob and Faci (2010)

obtained a lack of energy closure equal to 26% in a drip-irrigated hedge-pruned olive orchard (f_c = 34%). Therefore, the literature shows a general lack of energy balance closure between 5% and 20% even under ideal fetch conditions (Twine et al. 2000; Wilson et al. 2002). Based on this problem, many sources of the lack of energy balance closure have been proposed, such as 1) errors in measurements, 2) incorrect accounting for the storage of energy in the soil and canopy, or 3) advective flux due to heterogeneities in vegetation cover, among others (Leuning et al. 2012).

In this study, the average value of r_a^c was 17 (± 5.2) s m^{-1} and 90% of data was $< 25 \text{ s m}^{-1}$. For r_a^a , the 88% of the estimated values were $< 10 \text{ s m}^{-1}$ reaching an average value of 6.2 (± 3.4) s m^{-1} . Additionally, 89% of the total observations were $< 300 \text{ s m}^{-1}$ for r_s^s and r_a^{bs} , which presented mean values of 159 (± 101) s m^{-1} and 164 (± 104) s m^{-1} , respectively. Estimated values of r_s^s were between 83 and 418 s m^{-1} , with an average value of 158 (± 53) s m^{-1} . Also, the Jarvis-type model subestimated daytime variation of r_s^s with an error of 1% while RMSE,

TABLE 3. Maximum, minimum, and mean values of air temperature T_a , soil temperature T_{soil} , vapor pressure deficit D at z_r , net radiation R_n , and wind speed u recorded in days during the model evaluation period.

	T_a (°C)	T_{soil} (°C)	D (kPa)	R_n (W m ⁻²)	u (m s ⁻¹)
Season 2009/10					
December					
Min	7.4	15.9	0.0	-75.0	0.3
Max	32.8	39.2	4.3	751.4	4.1
Avg	18.9	25.9	1.3	192.7	1.5
January					
Min	8.6	17.8	0.0	-69.4	0.3
Max	34.4	40.7	4.4	715.1	4.3
Avg	20.9	28.0	1.5	201.2	1.7
February					
Min	8.2	17.1	0.0	-60.1	0.3
Max	30.3	36.4	3.3	667.4	3.7
Avg	18.1	24.6	0.7	139.1	1.5
Season 2010/11					
December					
Min	4.4	13.2	0.0	-102.6	0.2
Max	32.5	29.6	4.4	764.1	3.4
Avg	17.7	21.7	1.0	186.7	1.4
January					
Min	8.4	17.5	0.0	-118.9	0.2
Max	34.0	33.2	4.7	735.7	4.7
Avg	21.1	26.2	1.4	189.7	1.6

MBE, and d_r were 41 s m⁻¹, 7.0 s m⁻¹, and 0.80, respectively (Table 4).

The validation indicated that the submodel estimated the R_n with values of RMSE = 65 W m⁻², MBE = -7.7 W m⁻², and d_r = 0.99. For the simulation period, the r_{oe} value was significantly different from 1.0, suggesting an overestimation of 6%. These results are in accordance to those reported by López-Olivari et al. (2015), who observed that three semiempirical models of R_n presented RMSE values ranging between 26 and 101 W m⁻². Major disagreements in the estimation of R_n are usually associated to the effects of cloudy days on the parameterization of ε_a , and the use of the uncalibrated Brutsaert's equation (Ortega-Farias et al. 2010). Additionally, non-representative α values could lead to inadequate estimations of R_n because it is the reflection coefficient for solar radiation (Jones 2013). Thus, using inadequate information may generate under/overestimation of the shortwave radiation available at the surface. On the other hand, the validation for G showed values of RMSE, MBE, and d_r equal to 49 W m⁻², 1.3 W m⁻², and 0.95, respectively. For G , Li et al. (2006) obtained RMSE values ranging between 22 and 25 W m⁻² over agricultural landscapes.

Using 30-min time intervals, Table 4 shows that the clumped model estimated the LE with RMSE, MBE, and d_r values of 35 W m⁻², -1.0 W m⁻², and 0.96, respectively.

FIG. 1. Regression analysis between turbulent fluxes ($H + LE$) from the eddy covariance and the available energy of the system ($R_n - G$). The solid line represents the 1:1 relationship.

In addition, the r_{oe} value was 0.89 and significantly different from the unity, indicating that the clumped model underestimated the LE measured using the EC system by 11%. In the interval $0 < LE < 250$ W m⁻², the points were close to the 1:1 line (Fig. 2), meanwhile LE values outside this interval exhibited higher scatter. The overall daily comparison between estimated and observed ET_a (Table 4) indicated that the clumped model was able to predict the daily water consumption with RMSE, MBE, and d_r values of 0.48 mm day⁻¹, 0.04 mm day⁻¹, and 0.64, respectively. Moreover, the r_{oe} value was significantly different from 1.0 indicating that ET_a was underestimated by 3.0%. Also, Fig. 3 shows that the points were close to 1:1 line for ET_a ranging between 1.15 and 4.10 mm day⁻¹. Also, 73% of the absolute differences $|LE_{\text{BR}} - LE_c|$ were lower than 30 W m⁻² (Fig. 4).

The sensitivity analysis of uncertainties in the input parameters is shown in Table 5. For the clumped model, the sensitivity of ET_a to uncertainties in C , z_o , z'_o , r_s^c , r_s^{bs} , and d_p was small. The greatest variations were between 6.0% and 11.0% for LAI and r_{stmin} , suggesting that the

TABLE 4. Statistical analysis of the clumped model to estimate directly latent heat flux (LE_c) and evapotranspiration (ET_a) of a commercial superintensive drip-irrigated olive orchard. Also, evaluation of submodels to compute the net radiation R_n , soil heat flux G , and canopy resistance r_s^c are included. Variable n is the number of observations, RMSE is the root-mean-square error, MBE is the mean bias error, r_{oe} is the ratio of observed to estimated values, and d_r is the index of agreement.

Variable	n	RMSE	MBE	r_{oe}	d_r
R_n (W m ⁻²)	2064	65	-7.7	1.06	0.99
G (W m ⁻²)	2064	49	1.3	0.93	0.95
r_s^c (s m ⁻¹)	20	41	7.0	0.99	0.80
LE_c (W m ⁻²)	2064	35	-1.0	0.89	0.96
ET_a (mm day ⁻¹)	47	0.48	0.04	0.97	0.64

FIG. 2. Comparison between latent heat fluxes measured by the eddy covariance system (LE_{ec}) and computed by clumped model (LE_c) over 30-min intervals. The solid line represents a 1:1 relationship.

FIG. 3. Comparison between actual evapotranspiration (ET_{ec}) obtained from the eddy covariance system and that computed by the clumped model (ET_c). The solid line represents a 1:1 relationship.

clumped model is sensitive to the parameters controlling the water vapor transfer from canopy to the atmosphere. Thereby, the sensitivity analysis suggested that the accuracy of the clumped model to simulate ET_a significantly depended on the measurements of LAI and the used r_{stmin} . In this regard, Villagarcía et al. (2010) indicated that the clumped model was very sensitive to errors in the values of LAI and r_{st} , which are included in the formulation of r_s^c . Additionally, they also observed important variations of the estimated ET_a related to the depth at which the soil water content was measured to the parameterization of r_s^s and r_s^{bs} . However, this study was not able to verify the importance of r_s^{bs} attributed by Were et al. (2008), who evaluated the clumped model over bush-vegetation and semiarid conditions. Additionally, Zhang et al. (2008) found good agreement between the ET_a estimated by the clumped model and measurements obtained by the Bowen ratio-energy balance system, but the difference between the observed and estimated values would be mainly affected by r_s^c and r_s^{bs} and the inaccurate estimates of energy components in the vegetation and soil. Finally, Poblete-Echeverría and Ortega-Farias (2009) found major disagreements of the clumped model related to the days after rainfall or under foggy conditions (soil surface became wet).

The proper performance of the clumped model could rely on the fact that LAI and water status were almost constant during both seasons as result of the agricultural management. Thus, this research could only be extended to orchards with the same training system, row orientation and irrigation system (drip irrigation) under semiarid

climate conditions. First, because the ET_a depends on the intercepted solar radiation by the canopy and soil, it may significantly change with variations of interrow width and the hedgerow orientation (Connor et al. 2014; Trentacoste et al. 2015). Second, the estimation of r_s^s and r_s^{bs} may be affected by the fraction of wetted soil f_w , especially, in the flood and furrow irrigation systems. In this case, submodels using as input f_w and soil texture are required to improve the estimation of r_s^s and r_s^{bs} . Finally, an appropriate r_{st} estimation is also needed, considering that there are differences of the stomata closure even at the cultivar level. Therefore, the practical application of the clumped model would be limited by a correct description of the canopy

FIG. 4. Distribution of the absolute difference between the observed and estimated values of latent heat flux (LE_{ec} and LE_c , respectively).

TABLE 5. Sensitivity analysis to actual evapotranspiration (ET_a) estimated by the clumped model. Values represent the percentage of deviation of the output ET_a for a $\pm 30\%$ change of the parameters.

Model parameters	-30%	+30%
Extinction coefficient (C)	-0.9	-1.0
Displacement height (d)	2.2	-4.6
Zero plane displacement (d_p)	-2.4	0.4
Leaf area index (LAI)	11.0	-6.0
Attenuation coefficient for wind speed (η)	-2.7	0.7
Roughness length of surface (z_o)	-1.4	0.7
Roughness length of bare substrate (z'_o)	0.0	-0.5
Aerodynamic resistance for covered soil (r_s^c)	2.0	-1.7
Aerodynamic resistance for bare soil (r_s^{bs})	1.3	-3.9
Minimum stomatal resistance (r_{stmin})	11.0	-7.0
Maximum stomatal resistance (r_{stmax})	1.0	-2.0
Zero roughness length of the surface (Z_o)	-0.9	0.1

architecture and the fractional cover, which takes into account the differences of the intercepted solar radiation by the canopy and the soil.

4. Conclusions

The clumped model was tested using an EC system installed above a commercial superintensive drip-irrigated olive orchard with a constant value of f_c (30%) and LAI ($1.32 \text{ m}^2 \text{ m}^{-2}$) during two consecutive growing seasons. The estimation of ET_a and LE by the clumped model agreed well with the measurements of the EC system on daily and 30-min periods, respectively. For the two seasons, the clumped model underestimated LE and ET_a with errors of 11.0% and 3.0%, respectively. In addition, submodels of R_n , G , and r_s^c estimated with errors less than 6%. Finally, the sensitivity analysis indicated that the ET_a estimated by the clumped model was significantly affected by variations of $\pm 30\%$ in the values of LAI and r_{st} .

These results suggest that it is possible to directly estimate ET_a using the clumped model, which was very sensitive to errors in the values of stomatal resistance and leaf area index. Future research will be concentrate on the effect of water stress on the parameterization of R_n , G , and r_s^c . Also, we will explore the application of the clumped model to flood-irrigated orchards where soil evaporation plays an important role in the water application.

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