Actual evapotranspiration and crop coefficient of sweet orange during the initial development phase in the Rio Largo region, Alagoas

Ricardo Barros Silva1* José Leonaldo de Souza2 Ricardo Araújo Ferreira Júnior2 Marcos Alex dos Santos2 Renan Cantalice de Souza3 Wellington Manoel dos Santos1

1Programa de Pós-graduação em Agronomia, Universidade Federal de Alagoas (UFAL), 57100-000, Rio Largo, AL, Brasil. E-mail: ricardoufal2010@gmail.com. *Corresponding author.
2Laboratório de Irrigação e Agrometeorologia (LIA), Centro de Ciências Agrárias (CECA), Universidade Federal de Alagoas (UFAL), Rio Largo, AL, Brasil.
3Laboratório de Manejo de Plantas Daninhas, Centro de Ciências Agrárias (CECA), Universidade Federal de Alagoas (UFAL), Rio Largo, AL, Brasil.

ABSTRACT: Determining actual crop evapotranspiration (ETa) is paramount for irrigation management. The principal measurement methods and physical models generally require crop and weather data that are not readily available. We determined the crop coefficient (Kc) of sweet oranges during the initial development stage and evaluated the performance of the Poulovassilis semi-empirical model coupled with a simple soil water balance for estimating the ETa. The ETa was inferred from the variation in the soil water content over time, measured by time-domain reflectometry. In the Poulovassilis model, the ETa is obtained by multiplying the crop evapotranspiration (ETc) by an adjustment coefficient (ca), which accounts for a reduction in the evapotranspiration caused by soil water depletion. Soil water storage was obtained using the daily and 10-day soil water balances, computed by considering inputs and outputs of water from the system. The empirical parameter, ca, was determined using inverse modeling. The optimal ca value obtained through inverse modeling was 0.05 and 0.03 for the daily and 10-day soil water balances, respectively. The model performed better for the daily soil water balance than the 10-day balance, with performance comparable with the other ETa models. Average Kc during the sweet orange initial crop stage was 0.85.

Key words: Citrus sinensis (L.) Osbeck, evapotranspiration reduction, water balance.

INTRODUCTION

Oranges are one of the most widely consumed fruits worldwide, either “in natura” or through derivatives, generating employment and income in the producing regions. According to the IBGE (2018), Brazil was the world’s largest orange producing country in 2017, with a harvest of 17.5 million tons that corresponded to 23.8% of the global production and a yield of 27.6 t ha⁻¹. Within Brazil, São Paulo is the largest producer (13.35 million tons), whereas Alagoas is the eighth largest producer (156 thousand tons), with a yield of 14.75 t ha⁻¹.

The climatic conditions of the coastal table land region of Alagoas (which is unlike the other Northeastern micro-regions) favor orange
crops’s climatic requirements (temperatures between 13 and 35 °C, annual rainfall between 600-1200 mm) (REUTHER, 1973; BEN MECHLIA & CARROLL, 1989), the region provides an adequate thermal availability (annual temperatures between 19 and 31 °C) and an average annual rainfall of 1818 mm. However, the rainfall distribution in this region is seasonal, with a dry season occurring during part of the year, which renders crop irrigation necessary (SOUZA et al., 2005).

Actual crop evapotranspiration (ETa), which occurs on a vegetated surface, regardless of the development stage or soil moisture conditions, and without any boundary conditions is one of the main variables assisting rational water management in agriculture. Complexity and operational costs of the direct or indirect measurement methods for Eta favor a more common usage of estimation models (BRUTSAERT, 1982; RANA & KATERJI, 2000). Eta estimation models can be either physical, such as Penman-Monteith’s (MONTEITH, 1981) and Shuttleworth-Wallace’s (SHUTTLEWORTH & WALLACE, 1985), or empirical/semi-empirical (ALLEN et al., 1998; POULOV ASSILIS et al., 2001). In the latter, ETa values are derived from the concept of crop evapotranspiration (ETc) — evapotranspiration that occurs in cultivation areas, under optimal management conditions, without soil moisture restrictions (ALLEN et al., 1998). Generally, ETc is estimated by the crop coefficient (Kc) — evapotranspiration from a hypothetical grass with a height of 0.12 m, albedo of 0.23, and a fixed surface resistance of 70 m s⁻¹ — by the crop coefficient (Kc) that is dependent upon the crop development stage.

Semi-empirical methods (e.g., FEDDES et al., 1978; ALLEN et al., 1998; POULOV ASSILIS et al., 2001) estimate the ETa by multiplying the ETc by a reduction factor (a dimensional, varying between 0 and 1), to account for the reduction on ETc due to soil hydraulic limiting conditions. Therefore, these models differ by the mathematical expression used for the reduction factor, the soil routine employed for maintaining the water balance, or the partitioning of evapotranspiration into transpiration and evaporation. Compared with other models (e.g., FEDDES et al., 1978; ALLEN et al., 1998), the model proposed in POULOVASSILIS et al. (2001) is simpler and requires only one input empirical parameter (responsible for the exponential decrease of the ETc), which is a function of soil water storage. Although, this model was satisfactory in estimating the ETa of corn, wheat, and cotton (POULOVASSILIS et al., 2001), its performance for other crops; e.g., fruit crops, such as sweet orange needs evaluation. Moreover, the empirical parameter for the reduction curve varies with the soil type, crop, and atmospheric demand, thus requiring an adjustment for these conditions.

Semi-empirical approach to estimate the ETa requires the determination of ETa and the crop coefficient. The former is commonly measured or estimated in meteorological stations. The latter, however, varies with crop type and development stage (ALLEN et al., 1998). Furthermore, for citrus species, experimental results show that Kc may vary with soil and climatic conditions, owing to the higher inner resistances to water transport (MARIN & ANGELOCCI, 2011). The Kc values for citrus for the mid-season stage are widely reported in literature (e.g., SEPASKHAH et al., 1995; MORAES et al., 2015), but Kc data for the initial development stage are still scarce. Therefore, Kc values during the initial stage of citrus development need to be evaluated for each local condition.

The objective of this paper was to evaluate the POULOVASSILIS et al. (2001) model in estimating the ETa, coupled with a simple soil water balance model, during the initial stage of sweet orange tree growth in the Rio Largo region, in the coastal tablelands of Alagoas. Additionally, the Kc was determined for the initial crop growth stage.

MATERIALS AND METHODS

The experiment was carried out in an orchard located in the experimental area of the Agricultural Sciences Center of the Federal University of Alagoas (CECA-UFAL), in the coastal table land region, municipality of Rio Largo, Alagoas, Brazil (geodesic coordinates: latitude 9º27’58.7”S, longitude 35º49’47.2”W, and altitude 127 m). According to the Thornthwaite classification (THORNTHWAITE & MATHER, 1955), the climate of the region is characterized as humid, megathermal, with moderate water deficiency in the summer and substantial water excess in the winter. The average annual rainfall is 1818 mm, the air temperature varies between 19.3 °C (August) and 31.7 °C (January), with an annual average of 25.4 °C, and the average monthly relative humidity is above 70% (SOUZA et al., 2005). The soil of the region is classified as a cohesive yellow clay Latosol, with a field capacity (Ωf) of 0.232 m³ m⁻³, permanent wilting point (Ωwp) of 0.139 m³ m⁻³, soil density of 1.50 g m⁻³, total porosity of 0.423 m³ m⁻³, and basic infiltration rate of 52 mm h⁻¹.

Ciência Rural, v.49, n.6, 2019.
Sweet orange plants grafted on lemon trees were transplanted on April 8, 2016, in a 1904 m² plot arranged into 7 cultivation lines with 16 plants each, totaling 112 plants (spaced 4×4 m). The experimental evaluation occurred between August 2016 and March 2017. Formation pruning was carried out in January 2017. During the experimental period, meteorological data were obtained from the CECA – UFAL automatic agrometeorological station. The ET₀ was obtained using the Penman-Monteith-FAO method (ALLEN et al., 1998).

The drip irrigation system was adopted in the orchard, using self-compensating drippers with a flow of 8 L h⁻¹. A wet bulb area of 0.65 m² was applied to convert the volume of irrigated water (L) into water in the soil (mm), the value for which was determined by testing values for the dimension of the wet area that were consistent with moisture readings recorded by the field sensors. Irrigation shift was fixed at 2-day intervals, based on the ET₀. The soil water content (θ, m³ m⁻³) was monitored using a TDR apparatus (Water Content Reflectometers Model CS616, Campbell Scientific) by horizontally installing two probes in the 0–30 cm depth layer of the soil adjacent to two evaluated plants. The effective depth of the crop root system was assumed to be 0.3 m, considering that the orchard was composed of young plants. The θ data obtained by the TDR apparatus were adjusted to a second-degree polynomial equation, relating the θ and dielectric constant obtained by the TDR.

The ET on rainfall-free days was obtained from the variation in the soil water storage (W, mm) (RANA & KATERJI, 2000):

\[ \text{ET} = \Delta W \]  

where \( W \) is 1000 θ Zr, with Zr (0.3 m) being the effective depth of the root system and 1000 being the unit conversion factor (from m to mm). When θ was at field capacity, the ET was equal to ETc. For θ below the field capacity, the ET corresponded to the observed ETa (determined by the moisture variation obtained by TDR). The ETc values obtained from Eq. 1 allowed the determination of the crop coefficient (Kc), defined as Kc=ETc/ETa. These Kc values take into the account the wet area adjustment factor, since Kc was determined with ETa values (Eq. 1), minimizing the following objective function:

\[ \phi (\theta) = \sum (ET_a - ET_c)^2 \]  

where \( \phi(\theta) \) is the objective function to be minimized, \( ET_a \) are the observed ETa values (Eq. 1), \( ET_a(\theta) \) are the ETa values estimated by the Poulovassilis model coupled with the water balance, and \( ca \) is the parameter to be optimized. Function minimization was achieved through the non-linear generalized reduced gradient (GRG) method (WOLFE, 1963) using the Microsoft Excel solver tool.

Soil water storage was obtained through the daily and 10-day water balances (WB), counting the system water inputs and outputs, according to LHOMME et al. (1984):

\[ W_j = W_{j-1} + I_j - ET_a - D_j \]  

where \( I_j \) corresponds to the rainfall (mm), \( I_j \) (mm) to the irrigation, \( ET_a \) (mm day⁻¹) is the actual evapotranspiration estimated by the Poulovassilis model, and \( D \) (mm) is the drainage, obtained from the equation:

\[ D_j = \begin{cases} \left( P_{ij} - CR_j \right) ET_a & \text{if } P_{ij} - ET_a > CR_j \\ 0 & \text{if } P_{ij} - ET_a \leq CR_j \end{cases} \]  

where \( CR \) is the actual water storage capacity of the period (mm), obtained from \( W_{j-1} - W_{j-1}\).

The subscript \( j \) of Eqs. 4 and 5 indicates the day (or 10-day period) in which each variable was determined. The storage obtained by Eq. 4 was compared with the TDR-measured values.

The WB was started on a given day (or 10-day period), which occurred after a series of rainy days, where the soil water storage (W) was at field capacity. Thereby, it was possible to solve Eqs. 2 and 4, as the soil moisture at the beginning of the WB was known.

The performance of the model was evaluated by comparing the estimated Et values (for daily and 10-day WB periods) with the measured Et (obtained using Eq. 2) using the following statistical indices, as suggested by LEGATES and MCCABE JR. (1999): coefficient of determination \( r^2 \), data dispersion around the 1:1 straight line and its slope, Willmott’s index of agreement (d), Nash-Sutcliffe efficiency coefficient (E), and root mean square error (RMSE).

RESULTS AND DISCUSSION

The optimal \( ca \) values, computed by minimizing the objective function \( \Phi (ca) \) (Eq. 3),
were 0.05 and 0.03 for the daily and 10-day WB periods, respectively. These are well below the values suggested by Poulovassilis for cotton, maize, and wheat crops (ca=0.2). The ca parameter of the Poulovassilis model is related to the shape of the evapotranspiration reduction curve. For lower ca values, such as those obtained herein (ca=0.03 and 0.05), the reduction curve is ETa/ETc vs W is moderately reduced as W decreases (POULOVASSILIS et al., 2001). Low ca values are associated with low atmospheric demand for water, soils with high hydraulic conductivity, and/or plants that are more tolerant to water stress (POULOVASSILIS et al., 2001). Some experimental studies (e.g., CONSOLI et al., 2014; GASQUE et al., 2016) have indicated that orange crops have a tolerance to water stress (supporting pressure head values between -1.7 and 2.0 MPa). However, these studies preclude any inference on the shape of the evapotranspiration reduction curve and; therefore, one cannot infer whether the low ca values computed here are characteristic of sweet orange or caused by the effects of both the soil and climatic conditions. One way to investigate the characteristics influencing the ca could be to compare results of the Poulovassilis model to physical model simulations (after being calibrated for the crop), similar to modeling exercise by Santos et al. (2017). However, this is beyond the scope of this paper.

Although, the sensitivity analysis (Figure 1) indicated that the optimization was important to improve the Eta estimated by the Poulovassilis model, coupled with the simple WB, it was also observed that the Poulovassilis model is not very sensitive to the ca parameter at ca values around 0.2. For example, if one uses a ca of 0.2 instead of 0.05 (for the daily WB), the objective function increases by just 7.5%. Although, this sensitivity also depends upon the accuracy of the WBs used, it should be noted that the results suggested that tabled values for certain groups of crops, parameterized for some soil classes and atmospheric demands, are enough to apply the Poulovassilis model without greatly influencing its performance.

The model performance, concerning the estimation of the Eta for the daily and 10-day periods, is indicated by the statistical indices of table 1 and figure 2. In general, the daily WB model performed at a better level than did the 10-day WB model. The slope coefficient of line 1:1 of Figure 2 (b and d) indicated that, in general, the model underestimated the Eta during the evaluation period, and more so in the 10-day WB model. Conversely, the soil water storage was
overestimated both in the daily and 10-day scales and may be associated with the underestimation of the ETa.

The RMSE corresponds to the mean error of the estimates, being equal to 1.3 mm d⁻¹ and 1.25 mm d⁻¹ (mean daily value) for the daily and 10-day WBs, respectively. These values are comparable to values generated by other ETa estimation models (ERRAKI et al., 2009; RAN et al., 2017). The relatively high \( r^2 \) values indicate the precision of the model, while the values of \( E \) are related to accuracy. The \( E \) values of 0.74 and 0.49 for the daily and 10-day WBs, respectively, are more aligned with the performance of the model than with the index \( d \) (>0.9), regarding the dispersion of the values around the 1:1 line and the RMSE values. Interpretation errors of the indices \( d \) and \( E \) are discussed in the study of LEGATES and MCCABE JR. (1999).

The average \( K_c \) for sweet orange during the initial growth phase was equal to 0.85 (Table 2). Similar values were obtained by other authors for this phase: 0.85 (DOORENBS & PRUIT, 1977) and 1.0 (PEREIRA & ALLEN, 1997). It is important to highlight that the \( K_c \) of citrus species, as observed by MARIN and ANGELOCCI (2011), may vary according to atmospheric demand. Under moderate to
CONCLUSION

The semi-empirical model proposed by Poulovassilis, coupled with a simple water balance, estimated satisfactorily the actual evapotranspiration of sweet oranges during the initial crop growth stage, with values of the $ca$ parameter equal to 0.05 (for the daily water balance) and 0.03 (for the 10-day water balance).

The crop coefficient obtained for sweet orange during the initial crop growth stage in the coastal table land region of Alagoas was 0.85.

ACKNOWLEDGEMENTS

To the Foundation for Research Support of the State of Alagoas (FAPEAL) and to the National Council for Scientific and Technological Development (CNPq).

DECLARATION OF CONFLICT OF INTERESTS

The authors declare no conflict of interest. The founding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results.

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### Table 2 - Monthly values for the crop coefficient (Kc) during the experimental evaluation period, along with the average for the first year of sweet orange cultivation.

| Month   | Monthly Crop Coefficient (Kc) |
|---------|-------------------------------|
| August  | 0.30                          |
| September | 0.31                        |
| October | 0.41                          |
| November | 1.28                         |
| December | 1.18                         |
| January  | 1.12                          |
| February | 1.22                         |
| March   | 1.05                          |
| Final Average | 0.85                        |

The authors contributed equally to this manuscript.
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Ciência Rural, v.49, n.6, 2019.

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