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AGROMETEOROLOGY
Short Communication

An R-package to track soil water deficits in the root zone: when and how much to irrigate

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ABSTRACT: Irrigated areas have expanded globally to support the increasing population and mitigate the impacts of climate change and variability. The crop water balance accounting in the root zone estimates soil water deficits by considering water inputs and outputs that impact crop yield. In this study, we developed the CropWaterBalance R-package to assist users in irrigation scheduling. The package offers functionalities for estimating the reference evapotranspiration through various methods and comparing their performances. By incorporating user-provided management-allowed depletions, the package calculates several agrometeorological parameters including crop evapotranspiration rates, soil water deficit in the root zone, and water stress coefficient. The package also provides recommendations for irrigation timing and net irrigation depth.

Key words: water balance, irrigation management, evapotranspiration, scheduling.

INTRODUCTION

Irrigated areas have increased throughout the globe to support the growing global population and mitigate the effects of climate change (Siyal et al. 2023). This scenario of increasing water demand under new (often adverse) weather conditions is particularly pronounced in developing countries across Africa and South America (IPCC 2022). As a result, there is an increasing need to promote water-saving strategies (Provenzano et al. 2013). In this context, the provision of open-source tools capable of assisting growers in deciding when and how much to irrigate is paramount for promoting efficient irrigation management. The crop water balance accounting (CWB), as described by Allen et al. (1998), provides a framework for monitoring soil water deficits in the root zone by considering water inputs and outputs that impact crop yield potential (Andales et al. 2012, Duiker and Imhoff 2023). The CWB is particularly suitable for sprinkler irrigation systems. In practical terms, potential water depletion in the root zone is regarded as the crop water requirement. Plants aim to satisfy this water requirement using rainfall, stored soil water, and net irrigation. Therefore, rainfall, available water capacity of the soil (AWC), and crop evapotranspiration (ETc) are key inputs for the CWB. Rainfall is a natural water input to the root zone. The ETc represents a potential water requirement in the root zone, which occurs only at the following standard conditions: well-fertilized, healthy, free of biotic stress crops, grown in large fields under no soil water restriction, and achieving potential yields (Allen et al. 1998).

Daily rainfall data for the CWB are usually obtained from weather stations or other data sources such as satellite remote sensing platforms. ETc rates are frequently estimated using reference evapotranspiration (ET0) and the crop coefficient (Kc). The ET0 represents the combined process of evaporation and transpiration, which occur from a hypothetical grass reference crop under the standard condition as described for the ETc. Therefore, ET0 rates vary as functions of the meteorological elements, which modulate the evaporative power of the atmosphere. The AWC is the amount of water between the upper and lower storing water limits of the soil's layers. These upper and lower limits are called field capacity (FC) and permanent wilting point (PWP). The AWC of each soil layer is a function of its physical properties and soil management practices, and when multiplied by the effective root depth results in the total available water in the soil root zone (TAW). It is important to notice that crops experience drought stress before soil water depletion reaches PWP.

Thus, a management-allowed depletion (MAD), which is a fraction of TAW, should be specified. MAD values vary for each crop and across the growing season. TAW and Kc also vary across the crop's cycle in response to plant phenological changes.

On such a background, we developed the CropWaterBalance R-package to assist growers in irrigation scheduling using the water balance in the root zone. The package offers functionalities for estimating ET0 through distinct methods and computing water balance throughout the crop's phenological stages. Additionally, it includes auxiliary functions designed to compare the performance of different ET0 estimation methods. This feature is particularly valuable in regions where the availability of daily meteorological data is limited.

SOFTWARE DEVELOPMENT: THEORETICAL BACKGROUND

The Food and Agriculture Organization (FAO) Penman-Monteith method is recognized as the standard method for estimating daily ET_0 rates (Allen et al. 1998). Therefore, one of the key functions of the CropWaterBalance package is the ETO_PM() function that calculates daily ET_0 rates in millimetres using Eq. 1.

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \dfrac{900}{Tavg + 273} u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \tag{1}$$

where: R_n: the net radiation (MJ·m^{-2}·day^{-1}); G: the soil heat flux density (MJ·m^{-2}·day^{-1}); $Tavg$: the daily mean air temperature (ºC) at 2-m height, based on the average of maximum and minimum temperatures; u_2: the average wind speed at 2-m height (m·s^{-1}); e_s: the saturation vapour pressure (kPa); e_a: the actual vapour pressure (kPa); Δ: the slope of the saturated vapour pressure curve (kPa·°C^{-1}); γ: the psychometric constant (kPa·°C^{-1}).

Equation 1 requires several inputs, including the soil heat flux (G), a variable that is rarely measured. To address this, the package includes an auxiliary function called Soil_Heat_Flux(), which estimates G based on daily average air temperature values (Wright and Jensen, 1972; Eq. 2). Growers may use this function to estimate G and then proceed to apply ET0_PM(). Alternatively, growers may run ET0_PM() without providing the G argument. In this latter case, the function will default to using Soil_Heat_Flux() to estimate G and subsequently calculate ET_0.

$$G = 0.38\ (Tavg_i - Tavg_{i-3}) \tag{2}$$

where: i: the current day.

For regions lacking the necessary variables for calculating ET_0 using Eq. 1–a common situation in developing countries–, the package offers alternative methods, which require less inputs than the FAO method. Specifically, the functions ETO_PT() and ETO_HS() calculate the Priestley and Taylor (1972; Eq. 3) and Hargreaves and Samani (1985; Eq. 4) equations, respectively.

$$ET_0 = \alpha \frac{\Delta\ Rn}{\Delta + 2.45\gamma} \tag{3}$$

where: α: the Priestly-Taylor evaporative coefficient.

$$ET_0 = 0.0223 \times 0.4081633 R_a \times (T_{max} - T_{min})^{0.5} \times (T_{avg} + 17.8) \quad (4)$$

where: R_a: the extraterrestrial radiation (MJ·m^{-2}·day^{-1}); T_{max}: the maximum air temperature (°C); T_{min}: the minimum air temperature (°C).

The CropWaterBalance package also offers two functions, which may be used to evaluate the performance of nonstandard ET0 estimating methods. The Compare() function calculates various scalar measures of dispersion and accuracy between two numerical data samples, including the absolute mean error (AME), root mean square error (RMSE), original, modified, and refined Willmott's indices of agreement (d_{orig}, d_{mod}, and d_{ref}), and Pearson's determination coefficient (R^2). Additional information about these measures can be found in Wilks (2011) and Willmott et al. (1985). The Descriptive() function estimates summary statistics for a numerical data sample, including mean, median, standard deviation, standard error, maximum value, minimum value, and frequency of zeros.

The CWB() and CWB_FixedSchedule() functions calculate the crop water balance accounting and provide recommendations for irrigation scheduling. Central to these functions is the determination of soil water deficit (Di), which considers various factors, including the soil water deficit in the root zone on the previous day (D_{i-1}), crop evapotranspiration (ETc), rainfall (Rain), net irrigation (Irrig), flux of shallow groundwater in the root zone (U), surface runoff (SRO), and deep percolation (DP) on the current day (i). In many crop fields, the water table is significantly deeper than the root zone, leading to negligible flux of shallow groundwater (U ≈ 0). Additionally, the crop water balance approach assumes that when SRO and/or DP are greater than 0, there is no soil water deficit. Therefore, D_i can be calculated using Eq. 5 (Allen et al. 1998, Andales et al. 2012, Duiker and Imhoff 2023).

$$D_i = \begin{Bmatrix} \mathrm{D}_{i-1} + \mathrm{ETc}_i - \mathrm{Rain}_i - \mathrm{Irrig}_i, \quad \text{if } (\mathrm{D}_i + \mathrm{ETc}_i - \mathrm{Rain}_i - \mathrm{Irrig}_i) \geq 0 \\ 0, \text{if } (\mathrm{D}_i + \mathrm{ETc}_i - \mathrm{Rain}_i - \mathrm{Irrig}_i) < 0 \end{Bmatrix} \quad (5)$$

The ETc may be related to ET_0 by the K_c (Eq. 6), which expresses the difference in evapotranspiration between the crop and the reference grass surface when there is no soil water deficit in the root zone. The TWA (Eq. 7) is a function of AWC and Drz, and dmad expresses MAD in terms of depth of water in mm (d_{MAD}; Eq. 8).

$$\mathrm{ETc}_i = \mathrm{ET}_{0i}.\mathrm{Kc}_i \quad (6)$$

$$\mathrm{TWA}_i = \mathrm{AWC}_i.\mathrm{Drz}_i \quad (7)$$

$$\mathrm{d}_{MAD,i} = \mathrm{MAD}_i.\mathrm{TAW}_i \quad (8)$$

The CWB() function suggests irrigating when D_i reaches d_{MADi}. However, it is well known that this decision may be significantly influenced by the design and operation of the irrigation system, as well as the availability of labour and water. This is why the CWB_fixedSchedule() function allows growers to specify the number of days between consecutive irrigations. This latter function estimates the irrigation depth on these specific days. For both CWB() and CWB_fixedSchedule() functions, the value of Di is taken as the required net irrigation to be applied. Additionally, the CropWaterBalance package assesses the effect of Di on the crop evapotranspiration rates. This assessment is performed by multiplying ETc by the water stress coefficient (Ks, Eq. 9) to obtain ETa (Eq. 10). Conceptually, ETa is the evapotranspiration rate of well-fertilized and disease-free crops, grown in large fields, with or without soil water restriction (Allen et al. 1998). Both functions also present daily values for the difference between ETc and ETa (ET_deficit). Finally, an initial D value ($D_{initial}$) should be specified to start the water balance accounting. The function InitialD() calculates $D_{initial}$ using Eq. 11, which relies upon measured soil water content (θ; Allen et al. 1998). Finally, the package has three data sets, which exemplify the inputs required by its functions. The DataForAWC has AWC values for several soil textures, DataForCWB has all the inputs required by CWB() and CWB-FixedSchedule(), and DataForSWB has θ_{FC} and θ_{PMP} values (soil water content at field capacity and permanent wilting point, respectively) for several soil textures. Further information regarding these data sets can be found in the package documentation.

$$Ks_c = \frac{TAW_c - D_c}{(1 - MAD_c)} \tag{9}$$

$$ETa_c = Ks_c ETc_c \tag{10}$$

$$D_{initial} = 1000\,(\theta_{FC} - \theta_{obs})Drz \tag{11}$$

where: θ_{FC} and θ_{obs}: the soil water content for the effective root zone at the field capacity and at the moment of the measuring, respectively, in m^3/m^3.

APPLICATION

We applied the CropWaterBalance package to a bean field (cv. IAC 1850) situated in the Agronomic Institute's experimental farm in Campinas, state of São Paulo, Brazil. The meteorological data were collected from a weather station situated at the same farm (22.87°S, 47.07°W, 664 m altitude). The field has silt clay soil with θ_{FC}, θ_{pwp}, and AWC of $0.392 \cdot m^{-3} \cdot m^{-3}$, $0.270 \cdot m^{-3} \cdot m^{-3}$, and 122 mm, respectively, for the top 0.4-meter depth. We used a Teros 12 soil humidity with sensors installed at 0.2- and 0.4-m depth to measure the soil water content from August 30, 2023 (when the crop was in the vegetative phase) to October 3, 2023 (Blain 2024a). All packages' functions used in this application and their outcomes are also presented in Blain et al. 2024b.

We initiated the package application using the ET0_PM(), ET0_PT(), and ET0_HS() functions to estimate daily ET0 rates. Then, the Compare() and Descriptive() functions were applied to assess how well the estimates obtained from the two alternative methods approach those from the ET0_PM(). The results indicated that the alternative methods cannot be used to calculate daily ET_0 amounts in Campinas. For instance, the values of the d_{mod} and d_{ref} were lower than 0.45 for both alternative methods, and the AME values for ET0_PM vs. ET0_PT and ET0_PM vs. ET0_HS (1.24 and 1.95 mm, respectively) represent approximately 50% of the average daily values of the ET0_PM estimates (3.0 mm; Blain et al. 2024).

To demonstrate the package's ability to assist growers in irrigation scheduling, we applied the CWB() function considering two scenarios. Scenario 1 corresponded to the real field conditions where no irrigation was applied; scenario 2 corresponded to a hypothetical case where the package's recommendation about time and amount of irrigation were met. For both scenarios, the value for θ_{obs} (function InitialD; Eq. 11) was set to the average values of the soil water contents measured on August 30, 2023 at 0.2- and 0.4-m depth.

The CWB approach has been widely used for irrigation purposes. In this context, a high correlation level between the D values estimated by CWB() in scenario 1 (Eq. 5) and θ_{obs} is excepted. The linear correlation between D and θ_{obs} (Blain et al. 2024b) met this expectation by leading to an R^2 value larger than 0.9. This indicates that the package is able to assist growers in tracking soil water deficits in the root zone. In scenario 1, we also observed that the crop faced water stress for several days as indicated by the ET_deficit values (Fig. 1a). It is well known that this condition may prevent the crop from achieving its potential yield. In scenario 2, we applied the first irrigation on September, 2 (14 mm), as recommended by the CWB() function. After that, we applied irrigations in September on days 10 (13 mm), 17 (9 mm), 22 (13 mm), 24 (9 mm), and 26 (10 mm). As depicted in Fig. 1b, this irrigation scheduling led to virtually no crop evapotranspiration deficit, resulting in no water shortage in the root zone (ET_deficit values remained equal to 0 during the entire period).

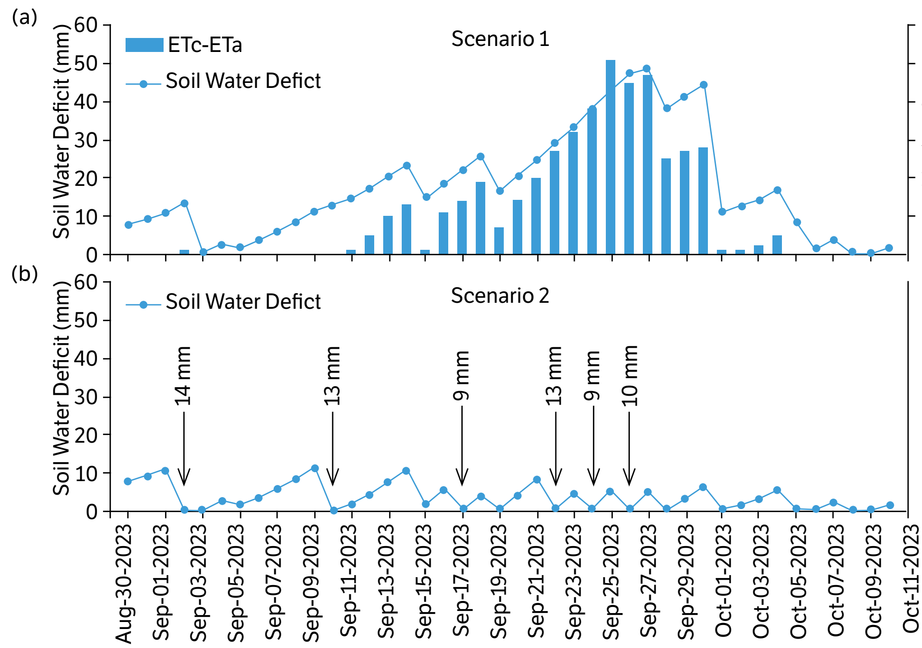

Figure 1. Using the CropWaterBalance R-package to make decisions about when and how much to irrigate. (a) Scenario 1 and (b) 2 represent a bean field (cv. IAC 1850) situated in Campinas, state of São Paulo, Brazil (22.87°S, 47.07°W). In scenario 1 no irrigation was applied. In scenario 2 the package's recommendation about when and how much to irrigate was met.

CLOSING REMARKS

The CropWaterBalance R-package helps growers calculate the crop water balance in the root zone, assisting them in making decisions about when and how much to irrigate. The package may be regarded as a flexible tool since it allows growers to specify, during all crop phases, water management parameters (e.g., management-allowed depletion and the number of days between consecutive irrigations), and other plant and soil factors (e.g., Kc and AWC). The package also assists growers in verifying the performance of alternative ET_0 estimating methods concerning reference models such as the FAO Penman-Monteith. Software availability is presented in Blain et al. 2024b.

CONFLICT OF INTEREST

Nothing to declare.

AUTHORS' CONTRIBUTION

Conceptualization: Blain, G. C. and Sobierajski, G. R.; **Investigation:** Blain, G. C., Sobierajski, G. R., Pires, R. C. M., Silveira, J. M. C. and Martins, L. L.; **Software:** Blain, G. C., Sobierajski, G. R. and Sparks, A. H.; **Validation:** Blain, G. C., Sobierajski, G. R., Pires, R. C. M., Silveira, J. M. C., Martins, L. L. and Sparks, A. H.; **Visualization:** Blain, G. C., Sobierajski, G. R., Pires, R. C. M. and Martins, L. L.; **Data curation:** Blain, G. C., Pires, R. C. M., and Silveira, J. M. C.; **Formal analysis:** Blain, G. C. and Sparks, A. H.; **Supervision:** Blain, G. C.; **Funding acquisition:** Blain, G. C. and Martins, L. L.; **Project administration:** Blain, G. C.; **Writing – original draft:** Blain, G. C.; **Writing – review & editing:** Blain, G. C., Sobierajski, G. R., Pires, R. C. M., Silveira, J. M. C., Martins, L. L. and Sparks, A. H.; **Final approval:** Blain, G.C.

DATA AVAILABILITY STATEMENT

The data are available in Zenodo in https://doi.org/10.5281/zenodo.13388512 and https://doi.org/10.5281/zenodo.13483903

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