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DOI: https://doi.org/10.1590/1807-1929/agriambi.v30n9e294838 ORIGINAL ARTICLE

Evaluation of canopy resistance models in the Penman-Monteith equation for evapotranspiration of cowpea[1]

Avaliação de modelos de resistência de dossel na equação de Penman-Monteith para evapotranspiração do feijão-caupi

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HIGHLIGHTS:

The Ortega-Farias model demonstrated high accuracy in predicting the hourly transpiration of cowpea.
The Lima equation achieved the best daily fit, with a strong correlation and a lower standard error.
Daily estimates were more precise when canopy resistance was derived from stomatal conductance.

ABSTRACT: Indirect methods for crop evapotranspiration (ETc) estimates are essential to improve water management in agriculture. Therefore, this paper aimed to evaluate the Penman-Monteith model using different canopy resistance approaches to estimate hourly and daily ETc for cowpea under climatic conditions in the northeastern region of the State of Pará, in the Brazilian Amazon. Evapotranspiration was directly measured using four drainage lysimeters to validate predictions from the Penman-Monteith method. Hourly evapotranspiration for cowpea was determined using the Bowen ratio-energy balance method. The Ortega-Farias model demonstrated high accuracy in predicting the hourly evapotranspiration of cowpea. The Lima equation achieved the best daily fit, with a strong correlation and a lower standard error. Daily estimates were more precise when canopy resistance was derived from stomatal conductance.

Key words: *Vigna unguiculata* (L.) Walp, Bowen ratio, lysimeter

RESUMO: Métodos indiretos para estimar a evapotranspiração de culturas são essenciais para o aprimoramento do manejo hídrico na agricultura. Assim, o objetivo deste estudo foi avaliar o desempenho do modelo de Penman–Monteith utilizando diferentes abordagens de resistência do dossel para estimar a evapotranspiração da cultura (ETc) horária e diária do feijão-caupi sob as condições climáticas da região nordeste do Estado do Pará, na Amazônia brasileira. A evapotranspiração foi mensurada diretamente por meio de quatro lisímetros de drenagem para validação das estimativas obtidas pelo modelo de Penman–Monteith, enquanto a evapotranspiração horária foi determinada pelo método da razão de Bowen–balanço de energia. O modelo de Ortega-Farias apresentou elevada acurácia na estimativa da evapotranspiração horária do feijão-caupi. A equação de Lima proporcionou o melhor ajuste para a escala diária, com forte correlação e menor erro padrão. As estimativas diárias mostraram maior precisão quando a resistência do dossel foi obtida a partir da condutância estomática.

Palavras-chave: *Vigna unguiculata* (L.) Walp, razão de Bowen, lisímetro

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Introduction

Cowpea (*Vigna unguiculata* L.) is one of the most cultivated crops in the northeastern region of the State of Pará, in the Brazilian Amazon. When growing cowpea crops, local farmers stand out for their use of technology and production planning. Among the resources used for crop planning in this region, agrometeorological models are an excellent tool (Farias et al., 2020; Moura et al., 2021; Carvalho et al., 2024).

Estimating evapotranspiration is a key component of agrometeorological modeling, as it is closely related to crop yield; moreover, accurate estimation is essential for effective water management (Sousa et al., 2021; Zhang et al., 2025a). The Penman-Monteith (PM) equation is a reference approach that, when combined with the canopy resistance variable (rc), can directly estimate crop evapotranspiration (ETc) under different atmospheric conditions and crop types (Ortega-Farias et al., 2004; Lima et al., 2006; Li et al., 2024).

Therefore, considering that ETc has high spatiotemporal variability (Khaydar et al., 2021) and that rc is sensitive to multiple environmental factors, as this variable controls the flow of water from the leaf mesophyll to the atmosphere, an accurate estimate of rc is needed for the crop in question (Zhang et al., 2025b), before associating it with the Penman-Monteith model.

Several rc models are limited, as rc can vary depending on several factors, such as climatic and genetic factors, making the models difficult to validate (Liu et al., 2020; Moura et al., 2021). Therefore, models developed in regions with similar climatic characteristics may be more efficient for calculating ETc (Venancio et al., 2021).

Ortega-Farias et al. (2000) proposed a model to estimate canopy resistance (r_{cl}, defined as the resistance to water vapor transfer from the leaf surface to the atmosphere at the canopy level) with the PM equation, using radiation balance, vapor pressure deficit, and soil water content. This model was tested in cowpeas (Lima et al., 2006), soybeans (Ortega-Farias et al., 2004), irrigated tomatoes (Ortega-Farias et al., 2000), and grass (Ortega-Farias et al., 1999).

Lima et al. (2016) calibrated and validated an empirical stomatal conductance (g_s) model for cowpeas based on temperature, solar radiation, vapor pressure deficit, and soil water content as a fraction of transpirable soil water in northeastern Pará. The equation proposed by Ortega-Farias et al. (2000) has performed well in several studies and continues to offer the advantage of estimating ETc at the hourly scale. Although the equation proposed by Lima et al. (2016) is used only at the daily scale, it may be more accurate and precise, as it was developed under similar climatic conditions to those of the present study region.

Therefore, this paper aimed to evaluate the Penman-Monteith model using the canopy resistance approaches of Ortega-Farias et al. (2000) and Lima et al. (2016) to estimate hourly and daily ETc for cowpea under weather conditions in the northeastern region of the State of Pará, in the Brazilian Amazon.

Material and Methods

The experiment was performed in Castanhal, PA, Brazil (1° 19' 24.48" S, 47° 57' 38.20" W, 41 m). The climate of this region is classified as humid equatorial (Af), according to the Köppen classification, with one to two dry months, mean annual rainfall around 2,200 mm, high air humidity during most of the year, and elevated temperatures, with mean annual values around 25 °C (FAPESPA, 2024).

Relative air humidity ranges from 79 to 95%. Total annual rainfall is around 2,561.6 mm, with 35% of this amount occurring from Jan to Mar, which is the rainiest quarter of the year. July to September is the driest quarter, and September is the least rainy month, accounting for only 4% of the total annual rainfall.

The experiment was conducted in 2013 and 2014, from Sept to Nov, in a 15,000 m^2 field. Cowpea – cultivar BR3Tracuateua – was sown mechanically, at a density of about ten plants per meter after thinning.

Fertilization was based on soil chemical analyses, which indicated the need for an initial fertilization of 10-60-40 kg ha^{-1} of NPK in 2013 and 0-40-45 kg ha^{-1} of NPK in 2014.

Crop height was measured daily, starting 10 days after sowing (DAS), considering crop phenological development. Leaf area was determined using the disc method (Sousa et al., 2022). The leaf area index (LAI) was measured weekly over the 60-day crop cycle from Sept to Nov and estimated from the relationship between leaf dry mass and leaf area.

Two agrometeorological stations were installed in the experimental area to measure weather, soil, and crop-related variables. Relative air humidity and temperature sensors were placed at two different heights from the crop canopy (0.5 and 2.0 m), and a CSAT3A sonic anemometer (Campbell Scientific Inc., USA) was placed at 2.5 m above the soil surface. Net radiation (Rn) was measured at 1.5 m above the soil surface with a CNR4 radiometer.

Soil heat flux (G) was measured using HFP01SC heat flux plates (Campbell Scientific Inc., USA) installed at different soil depths (0.10, 0.20, and 0.30 m below the ground surface). Volumetric soil moisture content (VSM) and soil temperature were measured using an array of three CS616 soil moisture reflectometers. These sensors present a measured water content accuracy of ± 2.5% VSM (this study used standard calibration with bulk electrical conductivity) and high precision (better than 0.1% VSM) (Campbell Scientific Inc., USA). Soil temperature was also measured using an array of three TCAV averaging soil thermocouple probes (Model 109), which consist of a thermistor encapsulated in an epoxy-filled aluminum housing (Campbell Scientific Inc., USA).

The instruments were set up in the center of the plot, with sufficient buffer zones (600 m) to avoid effects from adjacent areas on the measurements. All the above-mentioned sensors were connected to a CR10X datalogger (Powered by photovoltaic panels with a charge and discharge controller) (Campbell Scientific, Inc.) and an AM416 multiplexer (Campbell Scientific, Inc.). They were both programmed to

read the sensors every 10 s and to record the total and mean values of the readings every 10 min.

The plot/soil/crop/experimental site was irrigated using a drip irrigation system. Hydraulic checks were conducted before the experiment, with low-quarter distribution uniformity (DUIg) values of 96 and 94%.

Irrigation was performed daily to bring the soil to field capacity (FC) in each lysimeter, i.e., when water visibly drained from the bottom of the lysimeter. Irrigation depth was calculated as a function of weather conditions, the irrigation system's volumetric flow rate, and the lysimeter's surface area. Water replacement was calculated to provide a drainage depth corresponding to about 10-15% of the total irrigation depth.

Evapotranspiration was calculated using the Bowen ratio-energy balance method (ETcBR), based on the principles of energy conservation (Sousa et al., 2022; Silva Junior et al., 2023; Billesbach et al., 2024), according to the following Eq. 1:

$$R_n + LE + H + G + S_d + F = 0 \quad (1)$$

Where:

R_n - net radiation (W m^{-2});

LE and H - latent and sensible heat fluxes (W m^{-2}), respectively;

G - soil heat flux (W m^{-2});

S_d - energy stored in the canopy–soil system (W m^{-2});

F - energy used for photosynthesis; and,

S_d and F - were disregarded because they represent less than 1% of Rn.

Therefore, Eq. 2 became:

$$LE = \frac{R_n - G}{1 - \beta} \quad (2)$$

Where:

β – Bowen ratio, defined as the ratio between the vertical gradients of air temperature and actual vapor pressure (Perez et al., 1999).

The Bowen ratio (β) was calculated according to Eq. 3:

$$\beta = \gamma \frac{\Delta T}{\Delta e} \quad (3)$$

Where:

$\gamma = C_p P (0.622\lambda)^{-1}$ - psychrometric constant (kPa $°C^{-1}$);

C_p - specific heat of air (1013 J kg^{-1} $°C^{-1}$);

P - atmospheric pressure (kPa);

λ - latent heat of evaporation (J kg^{-1}); and,

ΔT and Δe - differences in air temperature (°C) and partial vapor pressure (kPa), respectively, between 0.5 m and 2.0 m above the crop canopy. Vapor pressure values (e) were calculated according to Allen et al. (1998).

Inconsistent data on β were excluded according to the criteria established by Perez et al. (1999). Therefore, values closer to 1 can be excluded, based on the accuracy of temperature and relative humidity measurements. Additionally, the criteria established by OrtegaFarias et al. (1996) were used, in which $\beta < -0.75$ are excluded.

After data validation, missing data were estimated. Energy flux data (H or LE) were collected as a function of the correlation found with available energy ($R_n + G$) for each phase. The most common hours for the occurrence of errors in the Bowen ratio method are at night, at dawn, and at the end of the afternoon; the latter two are due to changes in the sign of net radiation and soil heat flux (Perez et al., 1999).

Crop evapotranspiration was assumed to depend on the latent heat flux consumed throughout the day and was calculated according to Eq. 4:

$$ETcBR = \frac{LE}{\lambda} \quad (4)$$

Where:

ETcBR - crop evapotranspiration calculated by the Bowen ratio-energy balance method;

LE - latent heat flux; and,

λ - latent heat of water evaporation.

Evapotranspiration measured by drainage lysimeters (ETclys) was tracked daily by direct measurement, using four identical drainage lysimeters installed at the experimental site, with a volumetric capacity of 500 L, built from plastic conical water tanks, with the following measurements: upper and lower diameter: 1.20 and 0.98 m, respectively, and depth: 0.60 m. These measures are similar to those described by Farias et al. (2017).

During installation of the lysimeters, soil layers were carefully separated into horizons by manual digging to a depth of 60 cm and subsequently reassembled in their original order inside the lysimeters, under slight compaction to preserve the natural soil structure. After one month of installation, undisturbed soil samples were collected from both the experimental area and inside the lysimeters at the depths of 0–15, 15–30, 30–45, and 45–60 cm for physical analysis, as described below. Soil physical analysis indicated a sandy texture (70–74% sand, 13–17% silt, and 12–16% clay). Bulk density values ranged from 1.25 to 1.69 g cm^{-3}, with lysimeter values being 6–10% lower than those observed in the field. This slight reduction indicates minor loosening during packing; however, differences were consistent across depths, suggesting that soil packing preserved the original physical conditions to a satisfactory extent. Therefore, the lysimeter soil presented physical characteristics comparable to those of the field, minimizing potential biases in soil moisture measurements and supporting the reliability of the calibration curve used in this study. After three months, cowpea seeds were sown in the lysimeters, resulting in ten plants per meter and twenty plants in each lysimeter.

ETclys was calculated by water balance analysis, based on the inputs and outputs of water into and out of the lysimeter, according to Eq. 5 (Farias et al., 2017):

$$ETclys = P + I - D \quad (5)$$

Where:

P – precipitation (mm);
I - irrigation depth (mm);
D - drainage depth (mm); and,
ETclys - crop evapotranspiration.

Surface runoff and water capillary ascension were disregarded.

The estimate of evapotranspiration by the Penman–Monteith equation (ETcPM) was calculated according to Eq. 6 (Monteith & Unsworth, 1990):

$$ETcPM = \frac{\Delta(R_n - G) + \gamma E_a}{\Delta + \gamma(1 + r_c r_a^{-1})} \quad (6)$$

Where:
ETcPM - hourly crop evapotranspiration calculated according to the Penman–Monteith equation (mm h^{-1});
Δ - slope of the saturation vapor pressure curve as a function of air temperature (kPa °C^{-1});
R_n - net radiation (mm h^{-1});
G - soil heat flux (mm h^{-1});
E_a - aerodynamic transport of vapor (mm h^{-1});
γ - psychrometric constant (kPa °C^{-1}); and,
r_c and r_a - canopy and aerodynamic resistances (s m^{-1}), respectively.

E_a represents the combined effect of wind velocity, air temperature, and vapor pressure deficit on water losses and was calculated according to Eq. 7:

$$E_a = \frac{LE \cdot \varepsilon \cdot \rho_a \cdot VPD}{P \cdot r_a \cdot c_f} \quad (7)$$

Where:
VPD - vapor pressure deficit (kPa);
LE - latent heat of evaporation (J kg^{-1});
ρa - specific air density (kg m^{-3});
ε - ratio between the molecular weight of water vapor and the molecular weight of dry air (0.622);
P - atmospheric pressure (kPa); and,
C_f - conversion factor (680 W h m^{-2} mm^{-1}).

Aerodynamic resistance (r_a) was estimated according to Eq. 8, following the equation recommended by Allen (1989):

$$r_a = \frac{\ln\left[\frac{z_m - d}{z_{om}}\right] \ln\left[\frac{z_h - d}{z_{oh}}\right]}{k^2 U_2} \quad (8)$$

Where:
z_m - height at which wind velocity is measured (m);
z_h - height at which relative air humidity is measured (m);
d - zero-plane displacement height of the reference layer (m);
z_{om} - roughness length governing momentum transfer (m);
z_{oh} - roughness length governing heat and vapor transfer (m);
k - von Karman constant (0.41); and,
U_2 - wind velocity at 2 m height (m s^{-1}).

Zero-plane displacement height (d) and the roughness length governing momentum transfer (z_{om}) were estimated as a function of crop height (h_c) according to Eqs. 9 and 10, respectively (Brutsaert, 1982):

$$d = \frac{2}{3} h_c \quad (9)$$

$$z_{om} = 0.123 h_c \quad (10)$$

On the other hand, the roughness length governing heat and vapor transfer (z_{oh}) was estimated according to Eq. 11 (Brutsaert, 1982):

$$z_{oh} = 0.1 z_{om} \quad (11)$$

The slope of the saturation vapor pressure curve as a function of air temperature (kPa °C^{-1}) was determined according to Eq. 12:

$$\Delta = \frac{4098 e_s}{(T + 237.3)^2} \quad (12)$$

Where:
T - air temperature (°C); and,
E_s - saturation vapor pressure (kPa).

Canopy resistance (r_c) was determined using Eq. 13 to predict hourly ETcPM. This model is an attractive alternative for users of the Penman–Monteith equation because it requires readily available variables, such as vapor pressure deficit, radiation balance, and soil water content, which are easy to obtain and implement under field conditions.

$$r_c = \frac{\rho_a c_p DPV}{\Delta(R_n - G) c_f} F^{-1} \quad (13)$$

Where:
Cp - specific heat of air at constant pressure (1013 J kg^{-1} °C^{-1}); and,
F - normalized soil water content, ranging from 0 to 1.

The value of F was calculated as the relative soil water content according to Eq. 14:

$$F = \frac{\theta - \theta_{WP}}{\theta_{FC} - \theta_{WP}} \quad (14)$$

Where:
θ - soil water content measured using time domain reflectometers; and,
θ_{FC} and θ_{WP} - soil water contents at field capacity and permanent wilting point, respectively.

These values were determined in the laboratory using undisturbed soil samples and a Richards pressure chamber. The value of F in this study was equal to 1 for most of the experimental period. The r_c value was also obtained based on the value of g_s predicted according to Lima et al. (2016) (r_{cl}) for daily ETcPM predictions, as this model calculates g_s on a daily basis according to Eq. 15:

$$G_s = g_{sp} \times F_p \quad (15)$$

Where:

g_{sp} - potential stomatal conductance. Measurements of g_{sp} were obtained according to Eqs. 16, 17, and 18:

$$g_{sp} = 755e^{(-e^{-z}-z+1)} - 46 \quad (16)$$

$$z = \frac{prod - 0.021}{0.026} \quad (17)$$

$$prod = \frac{T \times VPD}{I_0} \quad (18)$$

Where:

T, VPD, and I_0 - mean values of air temperature (°C), vapor pressure deficit (kPa), and solar radiation (kJ h^{-1}) obtained from 11:00 to 13:00 h; and,

z - weighting factor that is a function of the product of meteorological variables (prod). The F_p factor represents the relative reduction of g_{sp} as a function of the currently available soil water content (F). F_p may range from 0 to 1, where 1 indicates optimal water availability, and 0 indicates that the soil is at the permanent wilting point, according to Eq. 19:

$$F_p = \frac{2}{1 + e^{(-5.9[F-0.009])}} - 1 \quad (19)$$

Stomatal resistance (r_s) was determined according to Vico et al. (2013), using Eq. 20:

$$r_s = g_s^{-1} \quad (20)$$

Then, r_{cl} was calculated according to FAO recommendations, in which r_c is calculated as a function of stomatal resistance (r_s) and leaf area index (LAI) of the crop.

Validation of ETcPM predictions using r_{co} and r_{cl} values was conducted by comparing them with the hourly and daily lysimeter values (ETclys). This comparison considers the ratio (b) between ETcPM, ETcBR, and ETclys. The Z test was used to determine whether b differs from 1.

Performance and efficiency assessments of the model were conducted using the following statistical tests: standard error (SE), agreement index (d), performance index (c), and coefficient of determination (R^2). The best results are associated with high values of d, c, and R^2, and low values of SE.

Results and Discussion

During the experiment, air temperature (28 °C) and relative air humidity (80%) remained close to the region's normal mean for this period of the year throughout crop development. Total rainfall during the experiment was 207.51 mm in 2013 and 160.00 mm in 2014 (Figure 1).

Despite differences in rainfall regimes between the two experiments, irrigation, along with rainfall during the experimental period, provided the crop with high soil water content and created conditions favorable to water loss through evapotranspiration. On rainless days, drip irrigation was performed in the late afternoon, with total irrigation depths of 285.58 and 268.39 mm in 2013 and 2014, respectively, at the end of each experiment.

Daily crop evapotranspiration was compared among the different methods (Figure 2). The regression equations were significant ($p < 0.01$), and only a few ETcPM values calculated with r_{cl} tended to exceed the observed ETclys values (Figure 2B),

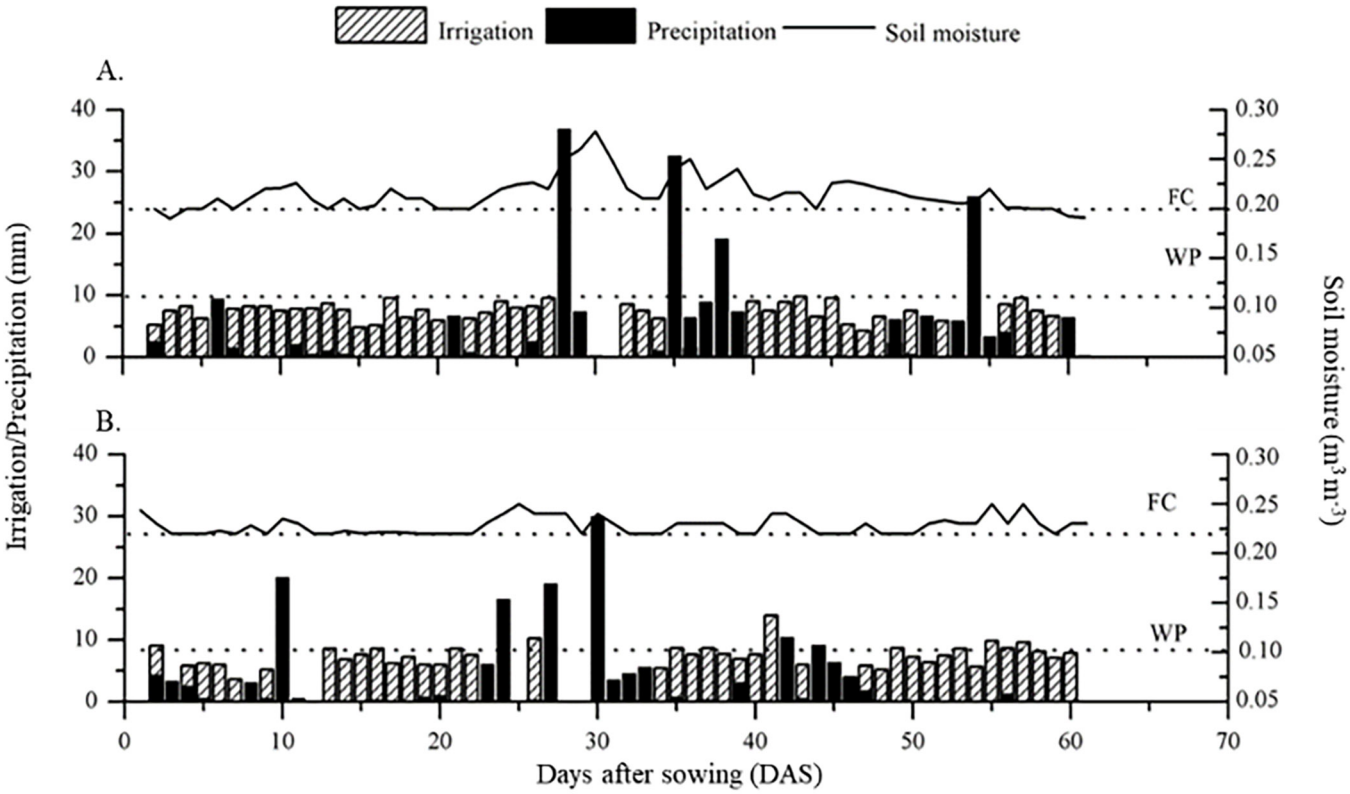


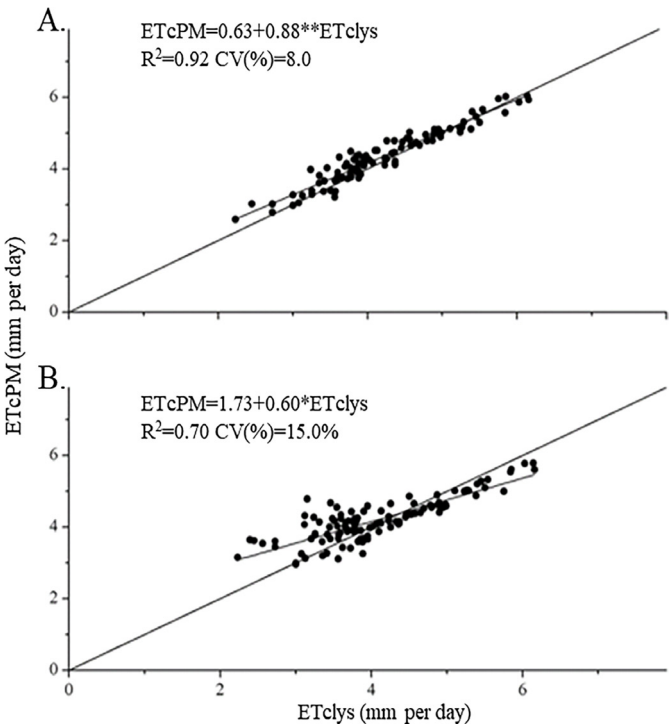
Figure 1. Irrigation, precipitation, soil moisture, field capacity (FC), and permanent wilting point (WP) throughout the cowpea crop cycle, expressed as days after sowing (DAS), in 2013 (A) and 2014 (B)

with an average overestimation of 2% or 4 mm. However, ETcPM calculated with r_{co} showed greater overestimation.

Cumulative evapotranspiration values throughout the crop lifecycle were calculated using ETcPM and r_{co}. The observed ETclys values were 254.04 and 247.93 mm, respectively. They indicate that the PM model overestimated the lysimeter data by 3% on average, corresponding to a cumulative difference of about 7 mm.

The PM model also overestimated crop evapotranspiration values for an ornamental species, New Guinea Impatiens (Morille et al., 2013). The authors concluded that overestimation occurs because the model considers only weather conditions above the crop canopy. They found a meaningful improvement in prediction quality when using weather data below the canopy level.

The ETcPM values calculated with r_{cl} are closer to the 1:1 ratio, with R^2 = 0.92, while those calculated with r_{co} show R^2 = 0.70. The lower R^2 value is due to higher ETcPM values with r_{co} at low LAI; therefore, the soil contributes a greater fraction of evapotranspiration. ETcPM values calculated with r_{co} were evaluated in two periods: LAI ≤ 1 and LAI > 1, to assess the model's performance under both conditions (Ortega-Farias et al., 2004).



**Significant at p ≤ 0.01 and *Significant at p ≤ 0.05 by F test

Figure 2. Correlation between the crop evapotranspiration of cowpea measured with a lysimeter (ETclys) and predicted using the PenmanMonteith equation (ETcPM), with canopy resistance predicted by stomatal conductance according to Lima et al. (2016) (A) and as proposed by OrtegaFarias (2000) (B)

Table 1 indicates that the model's performance improves under conditions of higher canopy development (LAI > 1), suggesting that vegetation structure plays a key role in the model's ability to accurately represent evapotranspiration processes. Under these conditions, the canopy becomes the dominant interface controlling water vapor exchange, and stomatal regulation exerts a stronger influence on fluxes (Cao et al., 2024; Rocha et al., 2025). Consequently, the Penman–Monteith model is better able to reproduce the physical and physiological controls governing evapotranspiration.

In contrast, for LAI ≤ 1, the reduced canopy cover increases the relative contribution of soil evaporation, introducing greater variability and complexity into the system. In this context, the model proposed by Ortega-Farias et al. (2004), which does not explicitly account for LAI in estimating canopy resistance, may lead to an overestimation of evapotranspiration. This limitation arises because the model does not adequately distinguish between soil and canopy contributions, particularly under sparse vegetation conditions.

Furthermore, the findings of Xu et al. (2017) reinforce the importance of properly parameterizing canopy resistance (r_c) to achieve accurate evapotranspiration simulations. The results of this study go beyond purely statistical improvements and highlight a structural limitation of the model under low LAI conditions. Therefore, incorporating biophysical variables that explicitly represent canopy development is essential to improve model robustness and ensure its applicability across different phenological stages and environmental conditions.

According to the authors, high crop canopy values are a key assumption for the applicability of the PenmanMonteith model, as it assumes the crop canopy as a "big leaf". The "big-leaf" concept simplifies the canopy as a homogeneous layer in the Penman–Monteith equation. However, this assumption overlooks the structural complexity of forest canopies. In heterogeneous systems, especially tropical forests, variations in leaf distribution, radiation, and stomatal behavior lead to uneven energy and mass exchanges, potentially biasing evapotranspiration estimates (D'Acunha et al., 2024). Factors like canopy stratification, species diversity, and gaps further limit the validity of this approach. Therefore, while widely used, the Penman–Monteith model should acknowledge these limitations, and multi-layer or two-source models may offer more accurate representations in complex canopies.

The agreement index (d) was used to assess the model's accuracy. It shows good agreement between hourly and daily

Table 1. Statistics of the performance of the Penman-Monteith model for daily predicted evapotranspiration values of cowpea, calculated with r_{co} and r_{cl}, and for hourly values calculated with r_{co}

Method	LAI	d	SE	c	r^2	b	Z- Test
Hourly ETcPM r_{co}	-	0.991	0.07	0.943	0.92	0.86	F
Daily ETcPM r_{co}	LAI ≤ 1	0.990	0.83	0.680	0.47	1.14	F
Daily ETcPM r_{co}	LAI > 1	0.998	0.30	0.970	0.94	1.02	T
Daily ETcPM r_{cl}	-	0.998	0.28	0.960	0.95	0.98	T

ETcPM predictions. Lima et al. (2006) reported high accuracy when comparing predicted cowpea ETc values calculated by the Bowen ratio method with those calculated by the PM equation, using canopy resistance as proposed by Ortega-Farias et al. (2000), with d > 0.99. However, they evaluated crop evapotranspiration only from 23 DAS onward, when LAI was probably greater than or close to 1. The research presented optimal fits for daily ETcPM predicted with r_{co} over the crop lifetime period, during which the crop shows LAI > 1, with d of about 0.998, c of about 0.97, R^2 of about 0.94, and a standard error of about 0.30. However, these values are lower when LAI ≤ 1.

The best results for daily ETcPM were obtained with r_{cl}, which was possible because LAI was used to predict canopy resistance. Also, r_{cl} was calculated with a model for gs that had been previously adjusted and validated for cowpea in the Amazon Region. According to Merk et al. (2024), LAI, as an indicator of the extent to which soil is covered by the crop canopy, also affects r_c.

The reduction in model performance under LAI ≤ 1 highlights the limitation of the Penman–Monteith approach under sparse canopy conditions. At low LAI, the canopy is no longer the main interface controlling water vapor exchange, and soil evaporation becomes more relevant. As a result, the dominance of stomatal control is reduced, limiting the applicability of canopy resistance (r_c) parameterizations.

The better performance of daily ETcPM using r_c, therefore, depends on sufficient canopy development, in which LAI effectively represents leaf area and stomatal activity. Under low LAI, the assumption of a homogeneous canopy, inherent to the big-leaf approach, becomes less valid. This increases uncertainty due to heterogeneity in radiation interception, aerodynamic conditions, and energy partitioning, reducing model accuracy.

Figure 3 shows that the daily values predicted by the PM model (ETcPM) are very close to those calculated by the energy balance method (ETcBR), even though the model using r_{co} overestimates crop evapotranspiration at the beginning and end of the crop lifecycle when LAI ≤ 1.

For LAI > 1, the Z test indicates that the b ratio (1.02) is not statistically significant; i.e., the predicted ETcPM values calculated with rco are similar to the ETcBR values during the same period. Ortega-Farias et al. (2004) found SE = 0.47 mm per day and b = 0.97 for soybean, both of which were not statistically significant. On the other hand, the same method, when applied to tomatoes, produced a standard error of the estimate of 0.51 mm per day and an a/b ratio that differs from 1 (Ortega-Farias et al., 2000).

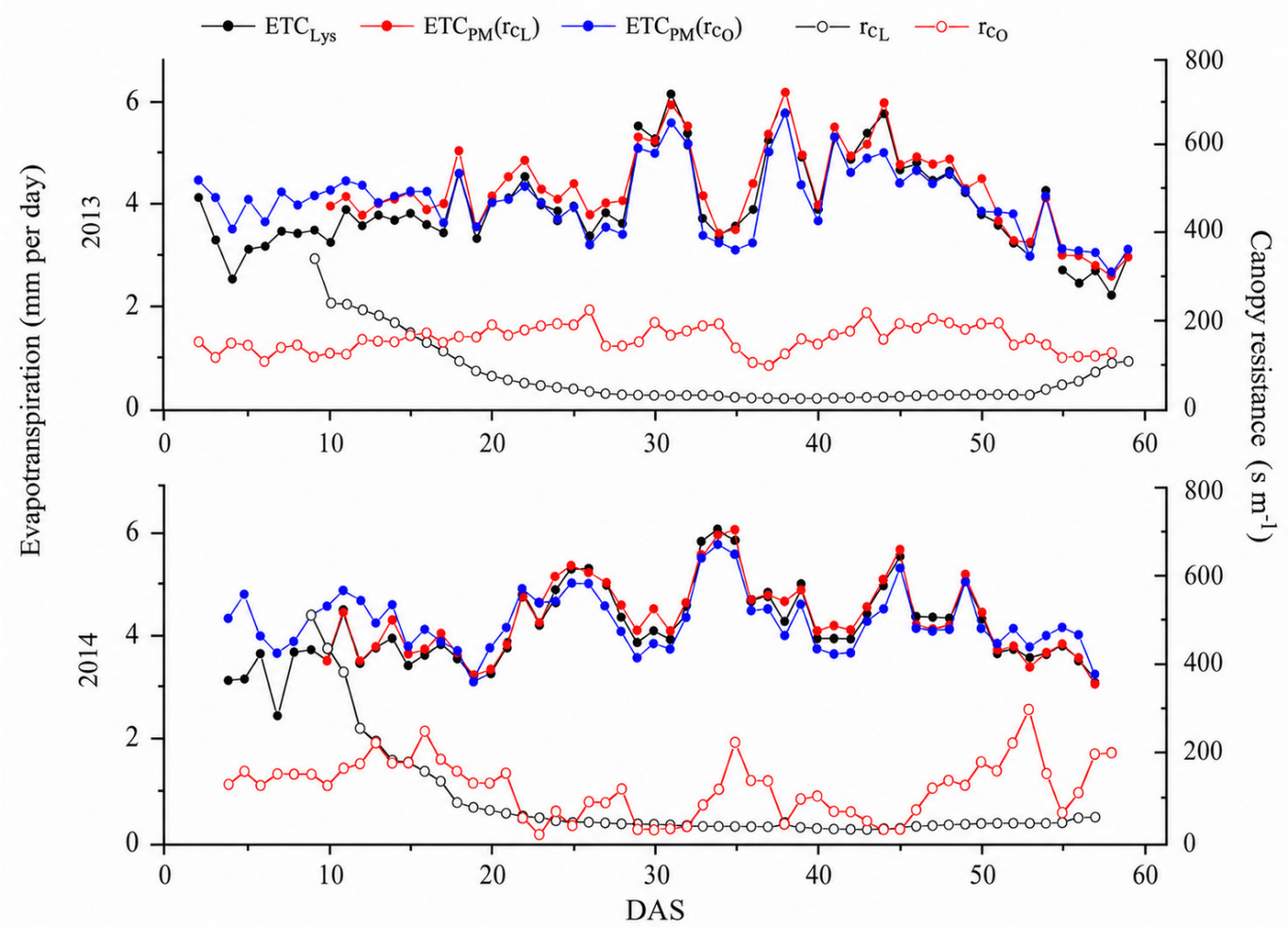


Figure 3. Daily cowpea evapotranspiration measured with a lysimeter (ETclys) and predicted by the Penman–Monteith equation (ETcPM) using canopy resistance proposed by Ortega-Farias (r_{co}) and canopy resistance estimated from g_s, according to Lima et al. (2016) (r_{cl})

The value of r_{co} shows greater variation as a function of VPD and R_n, whereas normalized soil water content (F) shows no significant change, suggesting that these weather-related variables are very important for controlling the physical process of evaporation (Ortega-Farias et al., 2004). The effect of VPD is widely accepted in the scientific literature. Its increase has direct effects on transpiration and on a consequent decrease of g_s. Under field conditions, the decrease in g_s is more closely related to a decrease in R_n (Lima et al., 2016).

Predicted values for g_s, using the equation of Lima et al. (2016), also vary in response to DPV and R_n. However, r_{cl} was calculated as a function of stomatal resistance (r_s) and leaf area index (LAI) of the crop. Thus, it showed smaller variations than r_{co}, as its variations are inversely proportional to those of LAI, with higher r_{cl} values at the beginning of the crop lifecycle, when LAI is lower.

These results indicate higher canopy resistance at the beginning and end of the crop lifecycle, when LAI is lower. Also, atmospheric conditions, such as wind speed and relative air humidity, strongly influence the transfer of water vapor to the atmosphere (Ghiat et al., 2021). On the other hand, evaporation from the soil is higher than transpiration because LAI values are low (Farias et al., 2017; Moreira et al., 2023).

Regarding the performance of the hourly Penman–Monteith model calculated with r_{co}, hourly evapotranspiration of cowpea showed values very similar to the predicted ones, with high values of d (0.991), c (0.943), and R^2 (0.92). Standard error for hourly values was equal to 0.07 mm h^{-1}. The results of the Z test show that b (0.86) differs from 1 at a 95% confidence level, indicating that ETcPM tends to be lower than ETcBR when considering an hourly step. Ortega-Farias et al. (2004) found similar results, with a standard error of 0.06 mm h^{-1} and $b \neq 1$ for soybean across a variety of soil and air moisture conditions.

The performance of the hourly PM model using r_{co} was assessed for different growth stages and under different meteorological conditions. Figure 4 shows hourly evapotranspiration during the vegetative and reproductive phases, as well as during physiological maturity, predicted by both the Bowen ratio–energy balance method (ETcBR) and the PM equation (ETcPM).

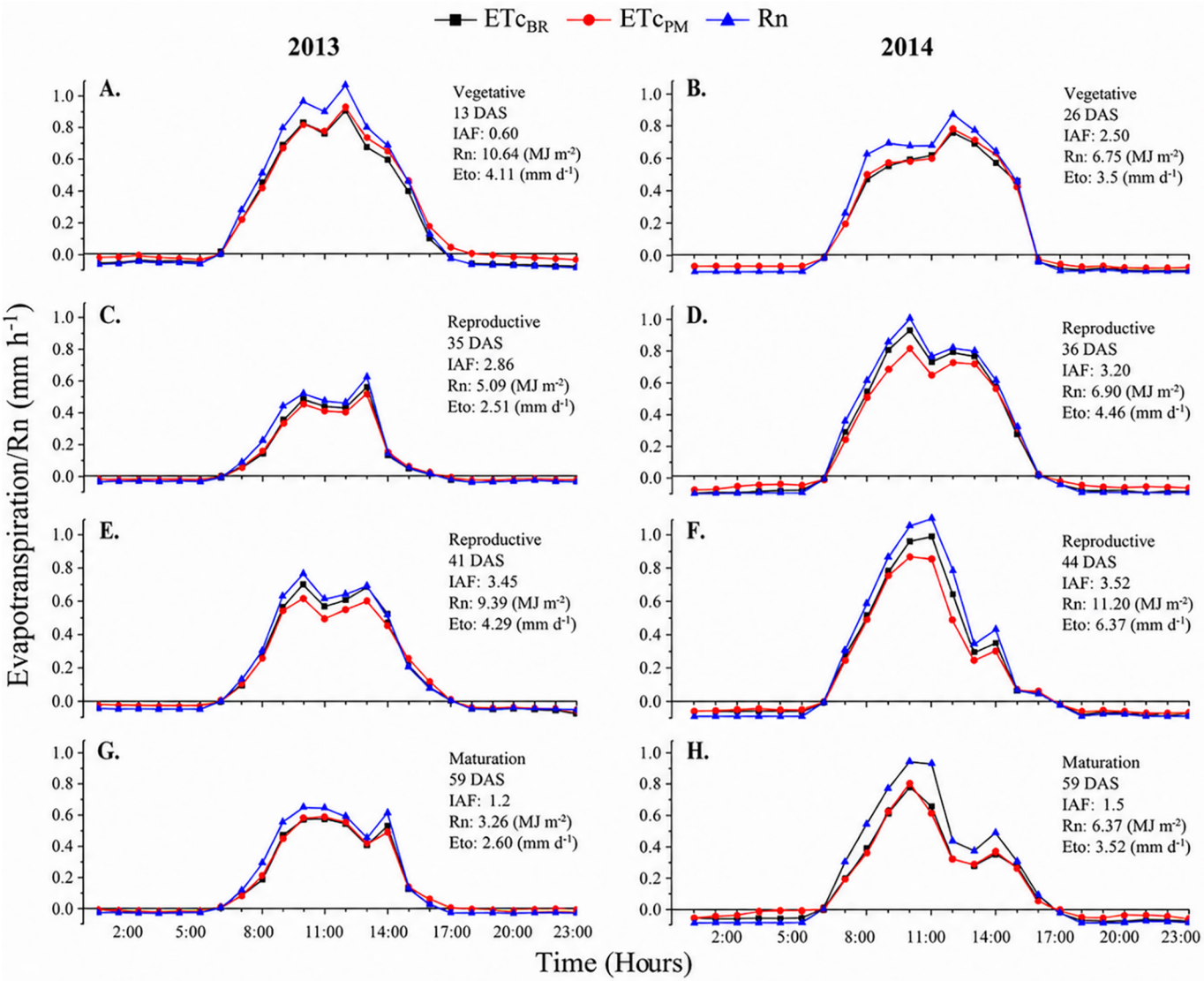


Figure 4. Hourly cowpea evapotranspiration predicted by the Bowen ratio method (ETcBR), Penman–Monteith equation (ETcPM), and net radiation (Rn) under different phenological stages and atmospheric conditions: A–B, vegetative stage; C–F, reproductive stage; and G–H, maturation stage, in 2013 and 2014

Although the analyzed days presented different atmospheric conditions in both years, as shown by net radiation (Rn) and reference evapotranspiration (ET_0), soil water content was consistently high during the vegetative and reproductive phases and at physiological maturity (Figure 1). In such conditions, predictions of hourly ETcPM showed good agreement, and the same behavior was observed across different meteorological conditions and crop development stages.

The variables R_n, ETcBR, and ETcPM all decreased rapidly in 2013 at 35 and 59 DAS, and in 2014 at 26 and 44 DAS (Figure 4). This phenomenon may be due to cloudy days and rainfall on those days, as well as to high variations in crop stomatal conductance when light fades (Xu et al., 2017).

Across all analyzed climate conditions, Rn strongly affected both ETcPM and ETcBR, and its diurnal behavior closely follows the energy availability curve. Xu et al. (2017) also reported that crop evapotranspiration values, both observed and simulated (by the PM equation), are largely influenced by R_n and show the same variation behavior for all the phenological stages of rice, regardless of weather conditions, with a tendency to overestimation or underestimation at noon.

Throughout the vegetative phase, ETcPM values were similar to those of ETcBR, with agreement indices of 0.9964 and 0.9942 in 2013 and 2014, respectively. In the reproductive phase, ETcBR and ETcPM were also very similar, regardless of weather conditions. The whole day shows high precision in ETcPM predictions, with $d > 0.9905$, even though there was a tendency to underestimate the observed crop evapotranspiration (ETcBR) between 10h00 and 14h00 on days with higher atmospheric demand, as reported by Xu et al. (2017).

This pattern can be primarily attributed to the increase in vapor pressure deficit (VPD) during midday, which intensifies atmospheric evaporative demand. Under these conditions, plants tend to regulate water loss by partially closing stomata, reducing canopy conductance as a protective mechanism against excessive transpiration and hydraulic stress. Although the Penman–Monteith model incorporates surface resistance as a bulk parameter, it does not fully capture the dynamic and nonlinear stomatal responses to rapidly increasing VPD, especially under high radiation and temperature conditions.

As a result, the model may assume higher transpiration rates than those actually occurring when stomatal limitation becomes significant. This physiological control becomes even more critical in dense canopies (LAI > 3), where soil evaporation is negligible and transpiration dominates the flux. Therefore, the underestimation of ETcPM observed during peak hours likely reflects the model's limitation in representing the effective stomatal closure (or potential stomatal downregulation) induced by high VPD, rather than solely an effect of increased net radiation. This highlights the importance of explicitly accounting for plant physiological responses to atmospheric demand when applying physically-based evapotranspiration models under strong land–atmosphere coupling conditions.

Because leaf area index is greater than 3 during this phase, soil evaporation is so small that surface resistance provides a good approximation for the physiological parameters of stomatal resistance (Rahman et al., 2022). Therefore, underestimating ETcPM in this phase may be due to greater stomatal resistance, caused by an increment in net radiation in that period.

Lima et al. (2016) found that cowpea stomatal conductance decreased with increasing VPD. Farias et al. (2017) reported a linear relationship between the crop coefficient (Kc) and reference evapotranspiration (ET_0), in which Kc decreases as ET_0 increases, even when soil moisture is high, suggesting increased control of evapotranspiration through stomatal closure under these conditions. In other words, there is an increase in internal resistance to water transportation in cowpea when it is subjected to high atmospheric demand, even when the soil has significant amounts of water.

Xu et al. (2017) also found that crop evapotranspiration in rice was slightly higher than the simulated rate (using the PM model, between 11h00 and 13h00) during days when the soil was saturated and in periods of higher evaporation rates. The authors deduced that, because the PM model is a big-leaf model, the canopy is virtually the only source of water vapor during periods of higher LAI, and evapotranspiration is equivalent to crop transpiration.

During the reproductive phase, the crop uses more water in its physiological processes than during the previous phases, resulting in a mean value of 0.85 for the $ETcBR/R_n$ ratio and a value of 0.82 for the $ETcPM/R_n$ ratio. During the vegetative phase, it reaches values of 0.74 for the $ETcBR/R_n$ ratio and 0.76 for the $ETcPM/R_n$ ratio, indicating an increase in crop evapotranspiration during the transition from vegetative to reproductive phases.

Regarding the $ETcBR/R_n$ ratio, about 85% of net radiation is used for evapotranspiration during the reproductive phase. Such values are much higher than those found in the literature. Lima et al. (2006) reported $ETcBR/R_n = 0.82$ and $ETcPM/R_n = 0.74$ in the reproductive phase, and $ETcBR/R_n = 0.71$ and $ETcPM/R_n = 0.67$ in the vegetative phase in the microregion of Brejo Paraibano.

San José et al. (2003) reported an average LE/(Rn − G) ratio of 0.79 for the reproductive phase of cowpea in tropical savannas of Venezuela, i.e., 79% of the available energy was used for crop evapotranspiration. Lima et al. (2006) found an evaporative fraction [LE/(Rn − G)] of about 84% during the vegetative phase and 73% during the reproductive phase of rainfed cowpea in Pernambuco.

The high evaporative fraction was expected, as the total water supply, including rainfall and irrigation, reached a mean value of 386.04 ± 18.13 mm. By comparing this value with the total evapotranspiration rate in the same period, it becomes evident that cowpea did not suffer water deficit, and it received an extra amount of water of 138.11 ± 5.10 mm throughout the crop's lifetime. This differs from the studies cited above, which were conducted with rainfed crops subjected to varying soil water levels.

During phenological maturation (Figure 4), ETcBR and ETcPM were also very similar, with $d = 0.99$. In this phase, the crop is still using water for its physiological processes, but less than in the reproductive phase, as some leaves were

already senescent (Jha et al., 2018). Thus, the soil contributes to evapotranspiration.

Maximum E_a was 1.6 mm h^{-1} as a result of high air humidity (Figure 5). This is a low value compared to the one reported by Ortega-Farias et al. (2004) in France under Tropical Mediterranean climate conditions. The values of E_a were higher than 4 mm h^{-1}, in response to dry atmospheric conditions and windy days.

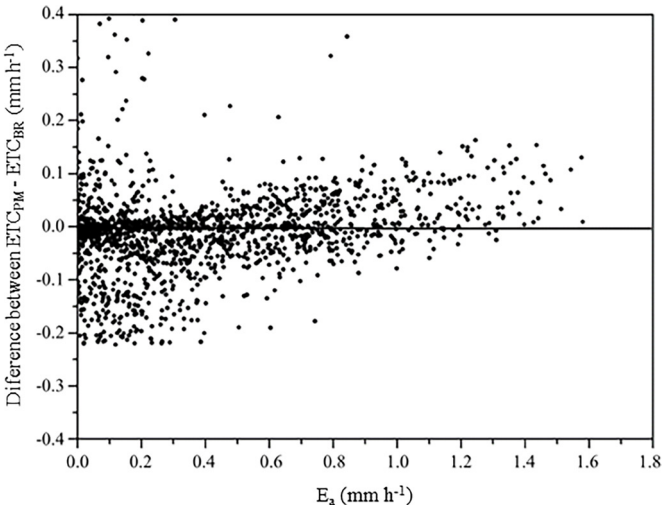


Figure 5. Differences between hourly evapotranspiration of cowpea obtained using the Penman–Monteith method (ETcPM) and the Bowen ratio–energy balance method (ETcBR) as a function of aerodynamic transport of vapor (E_a)

There were major differences between ETcPM and ETcBR when E_a was less than 1 mm h^{-1}. However, the frequency of these high absolute error values was below 1% (Figure 6). The most frequent absolute error corresponded to a difference of −0.02 mm h^{-1}, with VPD ranging from 0.04 to 1.62 kPa. Positive values started from E_a = 1 mm h^{-1}, with VPD ranging from 2.06 to 2.62 kPa.

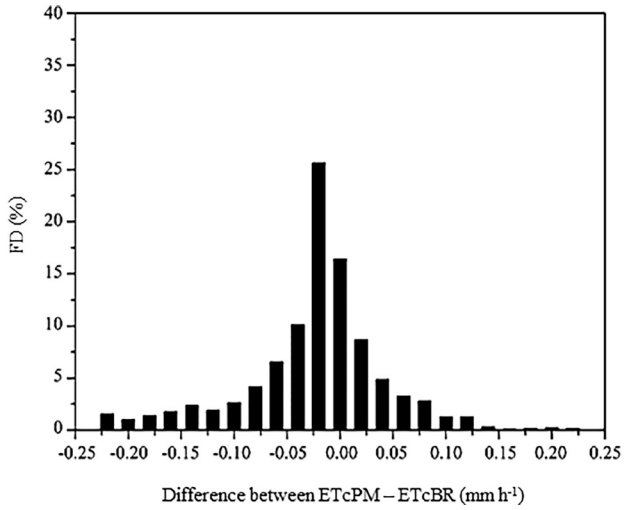


Figure 6. Frequency distribution (FD) for differences between hourly crop evapotranspiration of cowpea rates, calculated using the PenmanMonteith equation (ETcPM) and the Bowen ratio–energy balance method (ETcBR)

These results indicate that predicted ETcPM tends to be lower than the observed ETcBR when water vapor transport, VPD, and net radiation are lower, and relative air humidity is higher. Under these conditions, evapotranspiration becomes more dependent on aerodynamic interactions between plants and the atmosphere, suggesting that cowpea has greater canopy resistance, which reduces ETcPM predictions, even though soil water content is high. On the other hand, when Ea is greater than 1 mm h^{-1}, the plant is under weather conditions that favor lower surface resistance and higher ETcPM predictions.

Hourly ETcPM tends to be lower than ETcBR. However, major differences are rare, indicating that the Penman–Monteith model with canopy resistance (r_{co}) proposed by Ortega-Farias has a good fit for hourly evapotranspiration.

Conclusions

1. The Penman–Monteith model with canopy resistance parameterization effectively estimated evapotranspiration of cowpea across phenological stages and atmospheric conditions. Model performance was scale-dependent; the approach of Ortega-Farias et al. (2000) provided greater accuracy at the hourly scale, while the stomatal conductance-based parameterization (Lima et al., 2016) performed better at the daily scale.

2. Findings demonstrate that the appropriate selection of canopy resistance schemes according to the temporal scale is critical to improve model reliability. From an applied perspective, this scale-aware approach enhances irrigation scheduling, promotes more efficient water use, and supports more robust decision-making in agricultural water management under varying atmospheric demand conditions.

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