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Energy Balance, Water Demand, and Crop Coefficient of Acid Lime in the Oriental Amazon

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Abstract: Energy and water dynamics are crucial for citrus development in the Eastern Amazon. This study aimed to determine the energy balance, water demand, and crop coefficient of acid lime in the northeast region of Pará. A micrometeorological tower was installed in the center of the experimental area to monitor meteorological variables between October 2020 and December 2021. The energy balance and water demand were obtained by the Bowen ratio method. *Kc* was determined by the ratio between crop and reference evapotranspiration. The results obtained indicate that 63% of the available energy was used by latent heat in the rainiest period, while 60% was used during the less rainy period. Sensible heat used 32% and 34% during the most and least rainy periods, respectively. Soil heat presented a low variation, with an average of 5% for the entire period. Water consumption of the acid lime during the experiment was 1599 mm, with a daily mean of 3.70 mm day^{-1}, while the mean value of *Kc* was 1.4. These results allow for the design of adequate water supply protocols for the crop in the main citrus pole in the Amazon region.

Keywords: Bowen ratio; *Citrus latifolia*; decoupling factor; evapotranspiration

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1. Introduction

Brazil is the second largest producer of citrus in the world. Much of this production is aimed at the juice industry for export; however, citrus fruits are among the most demanded for fresh consumption, so there is a large market to be explored inside and outside the country [1,2].

The main national citrus production areas are concentrated in the Midwest, Southeast, and South regions. However, increasing production costs in these areas, combined with the maintenance of high productivity to serve the national and international markets, have provided the emergence of new citrus poles [3]. One of these is in the northeast of Pará. Stimulated by public policies, the opening of juice processing industries, a low incidence of pests and serious diseases, and the opening of new markets, the area has substantially expanded areas of cultivation [4–6].

Citriculture in Pará is located in the equatorial belt of the globe and, unlike other producing regions in Brazil, it is subject to specific production conditions in Amazonian environments. In this way, the local soil–plant–atmosphere interactions present variable responses unknown to the citrus crop in terms of energy balance and meeting water demand.

In order to obtain potential productivity in Tahiti acid lime crops, water supply to meet the local atmospheric demand, nutritional management, type of genetic material, and plant density must be taken into account [7]. Energy supply in the region and the architecture of the plant should also be taken into account, because the solar radiation absorbed by the plants is directly related to their efficiency in intercepting sunlight, making the canopy leaf density a determinant [8]. The amount of solar radiation interception by the leaves can also result in an increase in leaf temperature, sometimes causing photoinhibition [9], which can compromise crop productivity.

Plant controls in response to specific environmental conditions were observed by Coelho Filho et al. [10], who observed a lack of correspondence between sap flow and acid lime transpiration in Piracicaba (SP). According to the authors, transpiration in the morning follows the balance of available radiation (Rn), partially using the water stored in the tissues, while at the end of the day and at night, when transpiration decreases, the sap flow continues to occur at a rate that tends to replace loss of water from the tissues during the day.

Simon and Angelocci [11] highlighted that energy balance studies sometimes impose experimental difficulties. Therefore, these authors proposed the use of physical-mathematical equations capable of correlating the tree canopy radiation balance (Rnc) with the lawn radiation balance (Rng) and the global solar radiation (Rg), because these variables are more easily monitored and available.

The regional specificities of energy balance are inherent to terrestrial geography; as such, when studying energy balance, it is not possible to make broad generalizations because soil, plant, and atmosphere constantly interact [12]. In this context, Angelocci et al. [13] observed that at higher latitudes, high values of net radiation (Rn) were correlated with shortwave radiation at times close to noon in acid lime plantations and that radiation between different positions around the canopy during the day was crucial for light interception.

Energetic dynamics inside the plant canopy need to be better investigated, as their variation depends on the crop and the region and can be affected by several environmental and intrinsic factors of the plant [14]. These energy dynamics have been widely studied through the method of energy balance based on the Bowen ratio (BERB), mainly because it presents practicality and reliability in its results, even allowing the determination of ET_c [15–17].

When comparing the BERB with the covariance method of eddy vortices, it appears that the results of both present very similar values, as already verified in studies by Billesbach and Arkebauer [18] and Gavilán and Berengena [19], who concluded that the BERB, despite being a much less expensive and simpler method (as it requires few input parameters), demonstrates a high degree of accuracy and robustness in the determination of energy dynamics in several crops.

Understanding energy dynamics is essential to knowing plant water demand, which varies seasonally and phenologically [17]. Therefore, it is very important to determine the correct water level to be applied at different stages of the plant, as this can ensure flowering, setting, fruit growth, and quality, reduce the concentration of total soluble solids, and increase both the total acidity and the concentrations of sugars in the juice of citrus plants [20]. Pinto et al. [21] studied the partitioning of latent (λE) and sensible heat (H) fluxes over a lime orchard in Eastern Amazon during 2010–2021, and they observed higher λE than H from March to May (the wettest period). They also noticed that λE is driven by soil water available even with higher net radiation.

Knowledge about the crop's water demand can also reduce waste during its replacement through irrigation; as such, its determination is an indispensable tool for sustainable production [22]. Therefore, the objective of this study is to determine the energy balance, water demand, and crop coefficient in acid lime crops in the northeast region of Pará, Brazil.

2. Materials and Methods

2.1. Description of the Study Area

This study was conducted from October 2020 to December 2021 in a commercial plantation of Tahiti acid lime (*Citrus latifolia*) and Tanaka cultivar grafted on citrumelo (*Poncirus trifolia*, L.), located in the municipality of Capitão Poço in the state of Pará, Brazil (1°48′20.4″ South and 47°11′53″ West, 68 m altitude) (Figure 1). The soil of the experimental area was classified as Dystrophic Yellow Latosol [23] with medium texture. The soil's chemical and physical properties are in Table 1.

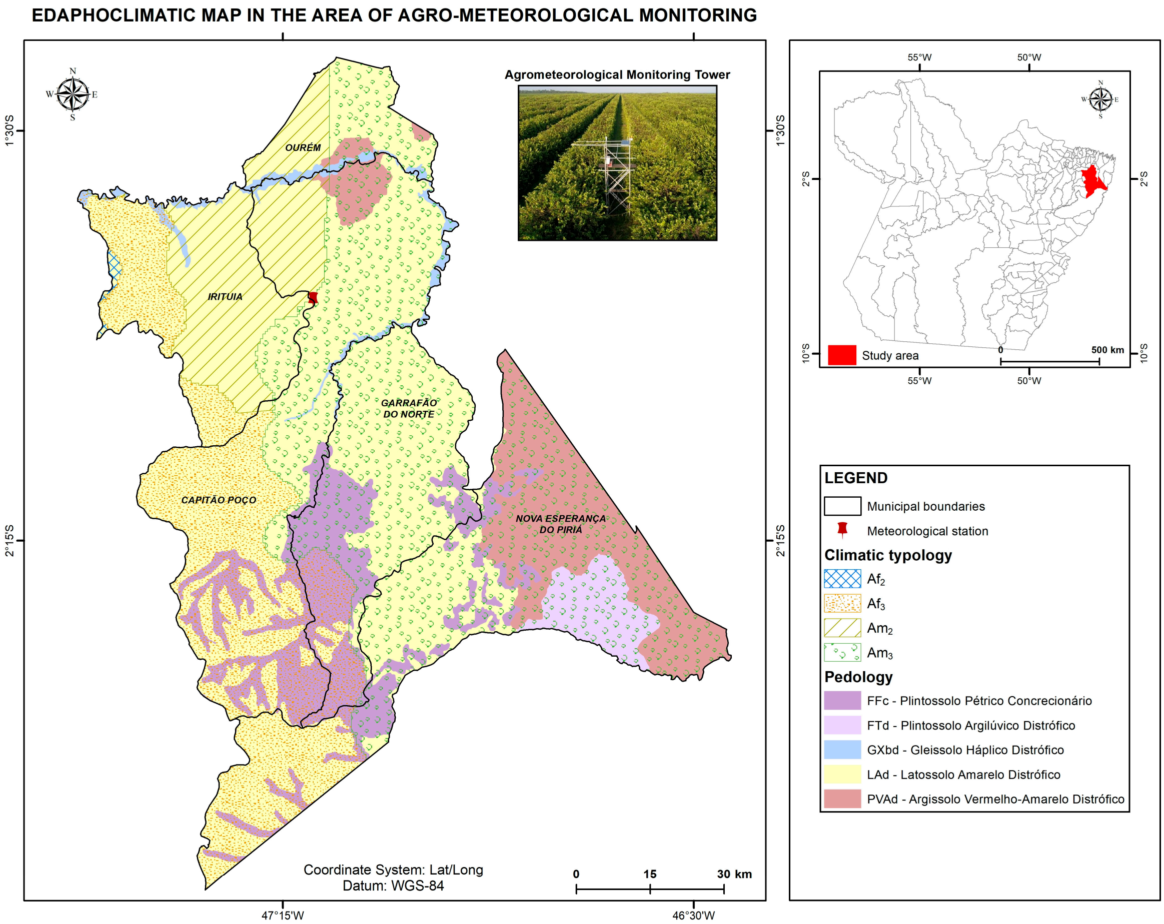

Figure 1. Location of the meteorological station of the experimental area in the municipality of Capitão Poço, northeast region of Pará. FFc and FTd: Plinthic subgroups (several classes of Oxisols, Ultisols, Alfisols, Entisols, Inceptisols); GXbd: Entisols; LAd: Oxisols; PVAd: Ultisols. For more information see Santos et al. [24].

Table 1. Soil chemical properties (0–20 cm) of the experimental site.

pH	P	K	Na	Al^{3+}	Ca^{2+}	Ca^{2+} + Mg^{2+}	H + Al	CEC		Saturation		Granulometry		
								Total	Effective	Bases	Aluminum	Sand	Silt	Clay
Water	mg dm^{-3}			cmol$_c$ dm^{-3}						%		g kg^{-1}		
4.85	15.55	14.57	8.39	0.98	0.66	0.1	2.74	3.57	1.81	23.35	54.03	750	120	130

Notes: pH = hydrogenionic potential; P = phosphorus; K = potassium; Na = sodium; Al = aluminum; Ca = calcium; Mg = magnesium; CEC = cation exchange capacity; V = base saturation; m = saturation by aluminum.

The local climate is characterized as tropical (Am) with a moderate dry season and average annual rainfall of 2500–3000 mm [17]. The experimental area has 12.5 ha, with plants spaced 2 × 6.8 m with 10 years of age. To support the identification of edaphoclimatic patterns in the study area, the map is shown in Figure 1, where it is possible to identify the five predominant pedological classes (Petric Plintosols, Argiluvic Plintosols, Argisols, and Gleysols, reinforcing that there is a predominance of Latosols Dystrophic Yellow) according to the map containing Brazilian soil classification [24,25]. It is also observed that the predominant climatic typology is Am2 and Am3, reinforcing that there are months with rainfall below 60 mm, according to the Köppen typology adapted by Martorano et al. [26] and also described in Martorano et al. [27].

In the study area, a drip irrigation system guarantees the replacement of water in the soil in periods of water deficits. The self-compensating emitters maintain a flow of 4.5 L h^{-1} each, with four emitters per plant distributed equidistantly from each other and located 0.5 m from the stem of the plants.

2.2. Determination of the Leaf Area Index (LAI) and Soil Cover Percentage (SCP)

To obtain the LAI, the leaf disc method proposed by Benincasa [28] was used, in which the leaves were perforated with the aid of a 2.84 cm^2 hole punch and leaf discs with leaf blade were highlighted, including the veins. The leaf discs of the known area of each leaf and the rest of the leaves were packed in paper bags separately. The collected materials were taken to an oven with air circulation at 65 °C until reaching constant weight to obtain the dry matter (g). Three plants were randomly selected for the collection of leaves and leaf discs. Subsequently, the dry disks and the rest of the leaves were weighed using a precision electronic balance with four decimal places. The leaf area (LA) was determined through the correlation between the dry weight of leaves (g), average weight of leaf discs (g), and leaf area (cm^2) of discs.

When the experimental area had a high density of planting, it was not possible to remove all the leaves from a single plant, because leaves and branches of neighboring plants were intertwined. As such, we sampled a certain canopy volume corresponding to 25%, which was used to estimate the total canopy volume in the entire area. LAI was calculated by relating the total leaf area to the total area of the experimental plot.

The total percentage of soil cover occupied by the crop was obtained at 50 random points within the experimental area, according to the methodology proposed by Bordignon et al. [29], through the average between the percentage of canopy coverage on the line and between the lines.

2.3. Determining the Effective Root Depth

Four trenches were opened in the experimental area at random points. Then root samples were taken every 10 cm (four repetitions of each depth) at depths from 0 to 110 cm. Afterwards, the samples were sieved to separate thick and thin roots. Next, the material was dried to determine the amount of roots for each depth extract to determine the effective depth of roots. The effective root depth for the crop was 60 cm.

2.4. Volumetric Soil Water Content

The volumetric soil water content was determined as a function of the matrix potential, obtained using tensiometers that were installed below the canopy at a distance of 1 m from the trunk and at a depth of 0.3 m. Undisturbed soil samples were obtained every 0.1 m up to 0.3 m as shown in Table 2.

The undisturbed samples were submitted to tensions of 1, 2, 4, 6, 10, 50, 100, 500, 1000, and 1500 kPa. Later, they were weighed to determine the remaining humidity with the aid of a high-precision balance. The data obtained were adjusted to van Genuchten's equation [30]; the coefficients of the equation are presented in Table 2.

Table 2. Coefficients of the van Genuchten equation adjusted to the effective root depth of Tahiti acid lime in Capitão Poço in PA.

Depth	$\theta_r = \theta pm$ ($m^3\ m^{-3}$)	θ_s ($m^3\ m^3$)	A	N	m	Θ_{FC} ($m^3\ m^{-3}$)	Apparent Density (g cm^3)
0.0 m–0.1 m	0.103	0.380	0.116	5.673	0.824	0.247	1.634
0.1 m–0.2 m	0.130	0.367	0.125	6.784	0.853	0.245	1.663
0.2 m–0.3 m	0.148	0.373	0.128	6.142	0.837	0.272	1.696

2.5. Measurements of Meteorological Variables

In the experimental area, data monitored in a 5.6-m high metallic tower were used, which contained automatic meteorological sensors connected to a CR1000 data logger (Campbell Scientific Instrument, Logan, UT, USA). Table 3 lists the installed sensors that make up the automatic weather station used in the experiment, as well as their arrangement in relation to the ground and canopy.

Table 3. Variables and instruments used in the experiment, as well as the arrangement of sensors in relation to the soil and plant canopy.

Meteorological Variables	Instrument, Maker, Model	Sensor Level (m)
Radiation balance	Radiometer balance (CRN4, Campbell Scientific Instrument, Logan, UT, USA)	2.0 above canopy
Wind speed	Anemometer (05106, Campbell Scientific Instrument, Logan, UT, USA)	2.0 above canopy
Rain	Rain Gauge (TB4, Campbell Scientific Instrument, Logan, UT, USA)	0.5 above canopy
Air temperature	Thermohygrometer (MX2301A, Onset computer corporation, Bourne, MA, USA)	0.5 e 2.0 above canopy
Relative air humidity	Thermohygrometer (MX2301A, Onset computer corporation, Bourne, MA, USA)	0.5 e 2.0 above canopy
Soil heat flow	Heat flow plate (HFP01SC, Campbell Scientific Instrument, Logan, UT, USA)	0.08 depth

The sensors used in the experiment were programmed to take readings every 10 s and total averages every 20 min. The location of the tower complied with the minimum requirements of the area's borders, presenting an available "fetch" (greater than the 1:100 ratio) so that the measurements obtained were representative of the experimental area without the influence of advective energy [31]. Effective rain was determined by using the CropWat software [32].

2.6. Energy Balance

The latent heat flux values were determined by the energy conservation law for the vegetated surface, using the Equation (1) based on the Bowen ratio:

$$Rn = LE + H + G + Sdv + F \tag{1}$$

where *Rn* is radiation balance; *LE* and *H* are the vertical flows of latent and sensible heat, respectively; *G* is soil heat flux; *Sdv* is energy stored in the vegetative canopy soil system; and *F* is energy used in the photosynthetic process.

The *G* component was estimated from two soil heat flux plates installed horizontally 0.08 m deep on both sides of the planting row (one below the planting row and the other between the planting rows), from which the average energy transported to the ground was obtained. The *Sdv* and *F* components were not considered in this study, as they represented less than 2% of the radiation balance [33].

The ratio proposed by Bowen [34] between the densities of sensible heat (*H*) and latent heat (*LE*) fluxes is widely used in the study of the partitioning of available energy.

Based on the Bowen ratio, the latent heat flux was obtained according to Equation (2):

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

2.7. Inconsistent Data Rejection Criteria of the Bowen Ratio Method

To reject inconsistent values provided by the Bowen ratio method, the criteria described by Perez et al. [15] were adopted, where the *LE* and *H* data generated by the BERB must show consistency in the flow–gradient relationship between the components, and where values of β close to −1 can be rejected due to the accuracy considered for the sensors, which in this study was 0.2 °C for the air temperature and 2% for the relative humidity of the air. These values were used to obtain the error—ε (Equation (3)) in order to determine the range close to −1 to be excluded.

$$\varepsilon = \frac{(\delta \Delta e - \gamma \delta \Delta T)}{\Delta e} \quad (3)$$

where γ is the psychrometric coefficient (kPa $°C^{-1}$); ΔT = T0.5–T2.0 air temperature differences above the canopy; and Δe = e0.5–e2.0 differences in water vapor pressure in the air layer above the canopy.

After quality control and exclusion of inconsistent data, gaps in energy flow data were filled in, correlating (H + LE) and ($Rn - G$) for each evaluation month [35], using the data from the correlation coefficients obtained monthly according to Table 4.

Table 4. Coefficient of regression analysis of the correlation between H + LE (Y coordinate) and $Rn - G$ (X coordinate), both in W m^{-2}, during the months of October 2020 and December 2021 in Capitão Poço in PA.

Months	Linear Coefficients		
	A	**B**	**R^2**
January	0.9689	3.0041	0.997
February	0.9762	−1.4033	0.999
March	0.9667	0.5605	0.998
April	0.9661	2.3443	0.999
May	0.9627	4.1186	0.998
June	0.9707	4.4476	0.999
July	0.9708	5.1420	0.999
August	0.9711	5.3684	0.999
September	0.9718	5.3904	0.999
October	0.9745	6.0228	0.999
November	0.9686	6.7263	0.999
December	0.9714	5.4151	0.999

2.8. Estimation of the Decoupling Factor, Evapotranspiration, and Crop Coefficient

Crop evapotranspiration (ET_c) was obtained using the Bowen ratio method through use of the diurnal and positive values of latent heat flux (*LE*). In this case, *LE* values obtained between 6.00 and 18.00 h were used in this study while energy was available (Rn-G > 0) [15]. ET_c values were estimated as follows (Equation (4)):

$$ET_c = \sum_{i=1}^{n=36} \frac{LE_i}{\lambda} \quad (4)$$

where ET_c is crop evapotranspiration (mm day^{-1}); LE_i is latent heat flux at 20 min intervals (W m^{-2}); and λ is latent heat in vaporization (J kg^{-1}).

The reference evapotranspiration (ET_o) was obtained by the micrometeorological method of Penman–Monteith FAO 56 [36], where the climatic data used in the estimation were obtained from the automatic meteorological station of the National Institute of Meteorology (INMET) located approximately 7 km from the experimental area.

After determining crop evapotranspiration and the reference evapotranspiration, the single crop coefficient (Kc) was obtained through the ratio between ET_c and ET_o, according to Equation (5):

$$Kc = \frac{ET_c}{ET_o} \quad (5)$$

The decoupling factor—Ω was obtained through Equation [37] based on the equation of Penman–Monteith, where values vary between 0 and 1. Values of Ω closer to 0 indicate that the variables of u2, RH, and VPD are controlling the transference of water vapor to the atmosphere, identifying in this case the vegetated surface as coupled with the atmosphere, while values closer to 1 designate that the greatest contribution in the evapotranspiration process is linked to energy in the form of solar radiation, characterizing the surface as uncoupled with the atmosphere (Equation (6)).

$$\Omega = \frac{1}{1 + \left[\left(\frac{\gamma}{\Delta \times \gamma}\right) \times \left(\frac{g_a}{g_s}\right)\right]} \quad (6)$$

where g_a, and g_s are the aerodynamic and surface conductances (s m^{-1}), respectively. To determine the g_a, microclimatic factors were considered and calculated by Equation (7):

$$g_a = \frac{0.4^2 u(z)}{\left[\ln\left(\frac{z-d}{z_0} + \phi_m\right)\right]^2} \quad (7)$$

where u is the wind speed (s m^{-1}) at measuring height z (m); d is the displacement of the zero plane (m); z_0 is the surface roughness (m); and ϕ_m corresponds to the wind profile correction factor, according to Fraga et al. [38].

To determine the g_s, the inverted equation of Penman–Monteith was taken into consideration (Equation (8)) according to the methodology described by Fraga et al. [38].

$$g_s = (r_s)^{-1} = \left[\frac{\rho_a c_p VPD}{\gamma\, LE} - \frac{1}{g_a}\left(1 - \frac{\Delta\, H}{\gamma\, LE}\right)^{-1}\right] \quad (8)$$

where g_s is the surface resistance (s m^{-1}); ρ_a is the air density (kg m^{-3}); c_p is the specific heat of humid air (1013 J kg^{-1} $°C^{-1}$); and H and LE are the values obtained by the method of the Bowen ratio.

3. Results and Discussion

3.1. Quality Control of Data Obtained by the Bowen Ratio Method

The results of the analysis of the quality control of the hourly data used in the energy balance by the method of the Bowen ratio are presented in Figure 2. It is observed that 67.58% of the data collected during the experiment showed consistency according to the methodology described by Perez et al. [15].

Throughout the experiment, it was found that at all times and months, inconsistencies were observed in the data generated by the Bowen ratio method, due to the low variability in the gradients of temperature and air humidity, predominantly in the early morning between 5:00 and 07:00 and in the late afternoon between 16:00 and 18:00 (Figure 2).

During the wettest period, there was a greater homogenization of inconsistent data, especially during the months of February, March, and April when there is an increase in errors between the hours of 11:00 and 15:00, due to the higher incidence of rains at these times that cause reductions in temperature and humidity gradients that are not favorable for the application of the Bowen ratio methodology.

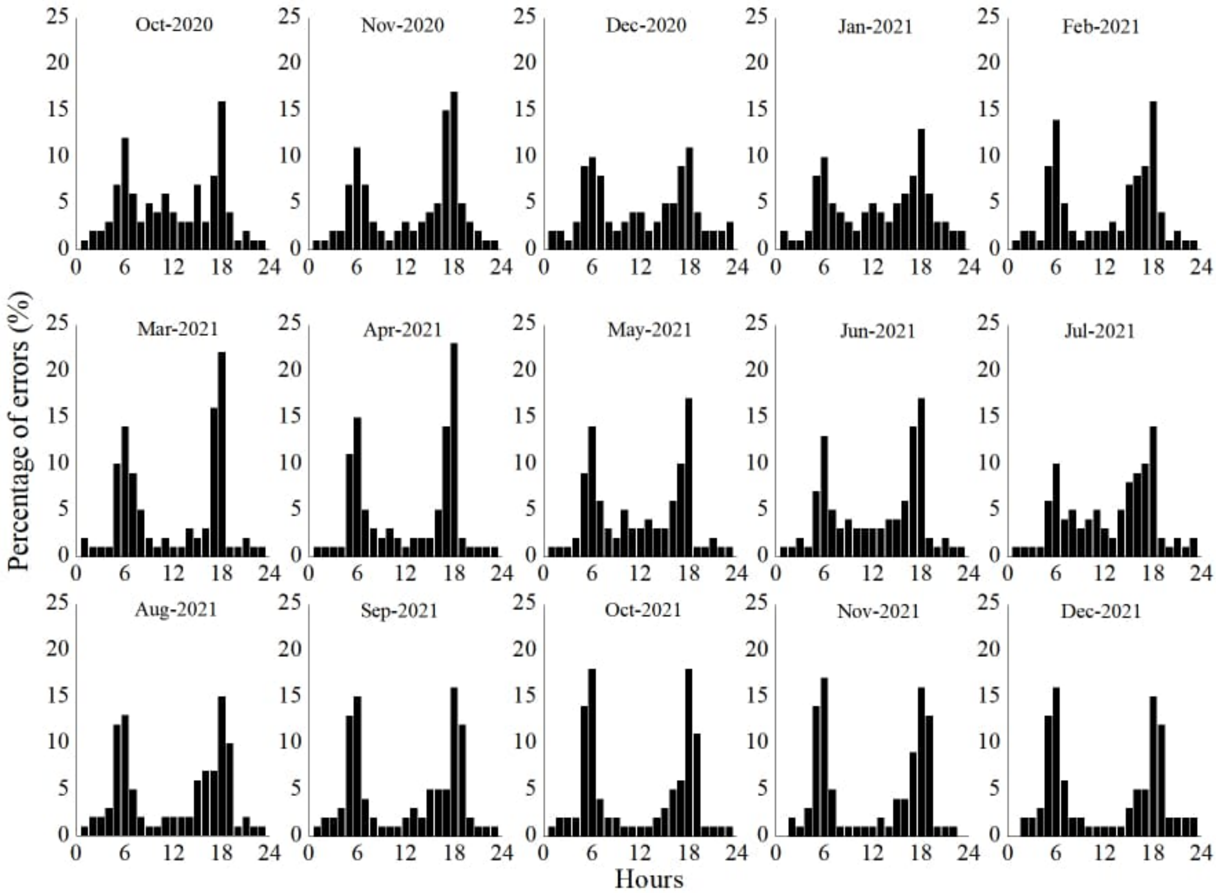

Figure 2. Percentage of time errors of the Bowen ratio method in different months of the year in Capitão Poço in PA.

3.2. Environmental Conditions and Variability of Volumetric Soil Water Content

Figure 3 shows the curves that demonstrate the variability of meteorological conditions that explain the evapotranspiration of vegetation cover. The average air temperature during the wettest period was 25.6 °C, while during the less rainy period the average air temperature was 26.4 °C, with absolute maximum (October) and minimum (January) ranging between 36.5 °C and 19.9 °C, respectively, during the period evaluated. Relative humidity showed an average variation of 1.1% between the most and least rainy periods, with a daily average of 86.9% and 85.8%, respectively (Figure 3a).

The temperature variability observed in the study area fits into the optimal condition for the development of Tahiti acid lime because the thermal range varies between 13 °C and 38 °C, which is considered favorable to the vegetative growth of citrus. In this range, citrus plants can emit new shoots to avoid heat stress [39].

The maximum vapor pressure deficit (VPD) and wind speed values (u2) observed in the experiment during the wettest period were 0.78 kPa and 1.11 m s^{-1}, respectively, while for the less rainy period the maximum values observed were 0.83 kPa and 1.36 m s^{-1} (Figure 3b).

Throughout the experiment, an inverse relationship was observed in the variability of climatic elements VPD, u2, and Tair when compared to the data of RH. This relationship was influenced by atmospheric conditions: when there was a higher demand for water vapor by the atmosphere, as in the less rainy season, the RH values reduced as the VPD values, u2, and Tair increased. Such behavior can induce an increasing gas exchange in the Tahiti lime canopy as long as planting presents soil water content under adequate conditions, which depends on the irrigation management installed in the area, as noted in the values expressed by the ET_o.

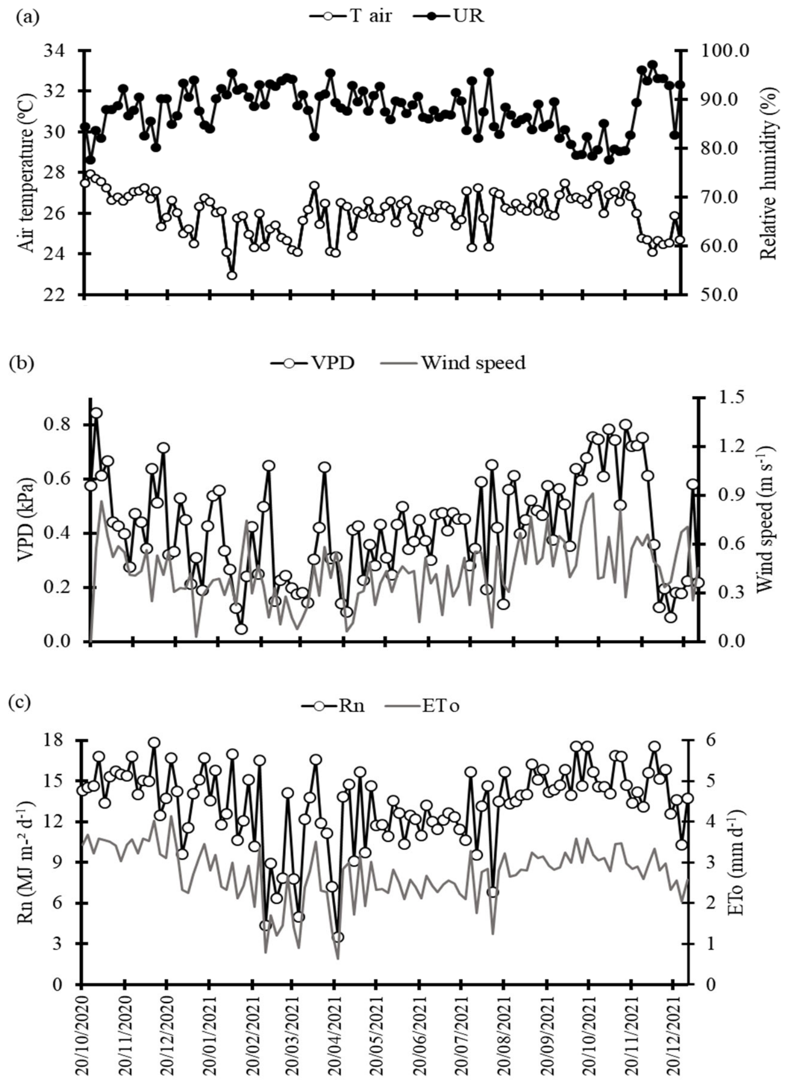

Figure 3. Variation of climatic elements of temperature and relative humidity of the air, (**a**) of the deficit of vapor pressure and wind speed and (**b**) of the net radiation and evapotranspiration of reference (**c**) over 15 months of experiment with Tahiti acid lime in Capitão Poço in PA.

During the rainiest period, the average values observed for *Rn* and ET_o were 12.20 MJ m^{-2} day^{-1} and 2.49 mm day^{-1}, respectively, while in the less rainy period the average *Rn* was 14.03 MJ m^{-2} day^{-1} and ET_o was 2.90 mm day^{-1} (Figure 3c). The higher *Rn* value in the less rainy period is due to the reduction of diffuse radiation, favored by the greater number of clear-sky days, which in turn culminates in an increase in the incidence of direct radiation, which increases atmospheric demand as it increases the Tair, VPD, and u2 values, also causing an increase in the values of ET_o.

The variability of the volumetric water content in the soil and rainfall over the 15 months of the experiment are observed in Figure 4. The volumetric content of water in the soil presented satisfactory conditions for the development of the crop, remaining above 0.21 m^3 m^{-3} and corresponding to the limit of readily available water (AFD) during the period between December 2020 and July 2021. This condition was mainly influenced by the fact that the period in question included 78% of the 3149 mm of rain that occurred during the experimental period.

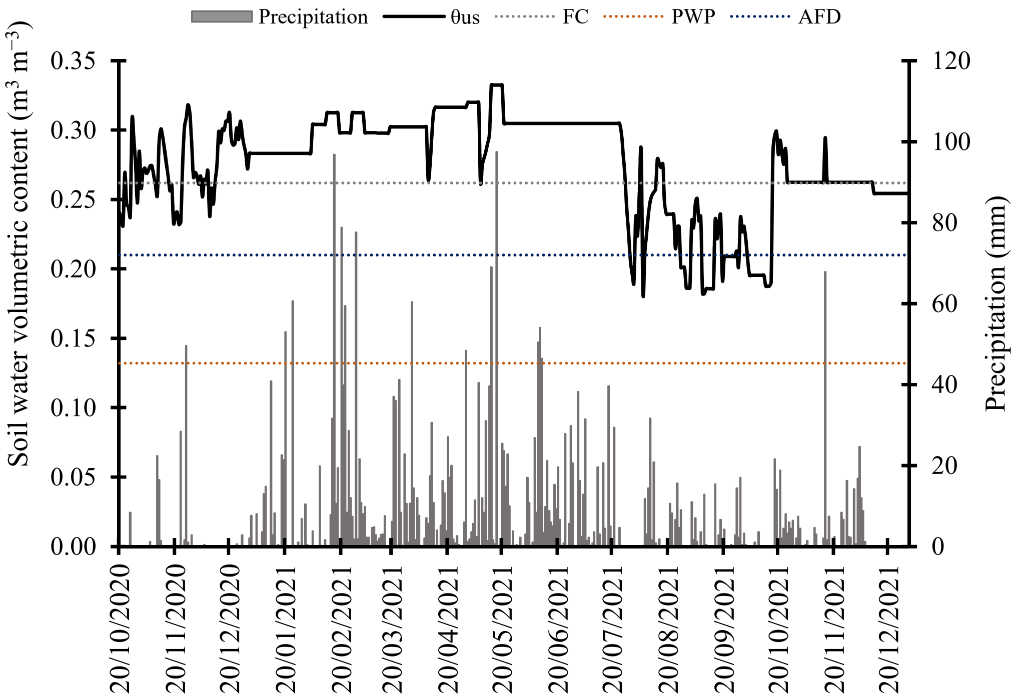

Figure 4. Variability of soil water volumetric content and precipitation over a 15-month experiment with Tahiti acid lime in Capitão Poço in PA. FC: field capacity; PWP: permanent wilting point.

During August and November 2021, the amount of rainfall corresponded to 22% of the total rainfall observed during the experiment (Figure 4). Despite this period having reduced volumetric content of water in the soil, it was found that the water level remained close to the limit of water easily available to plants (Figure 4), which is why the water supply was not carried out through irrigation. It is observed that the moderate reduction in the water available in the experiment during the less rainy period may have contributed to the flowering of the crop, since citrus in general has its flowering conditioned not only to internal stimulus, but also to environmental influences [40]. This was verified in a study by Alves Junior et al. [41], who, when meeting 25% of the water demand of acid lime in the phase that precedes the flowering of the crop, verified an increase in the amount of flowers, number of fruits per tree, and, consequently, its productivity.

The replacement of water by irrigation is an agricultural practice that can improve yield for citrus growers when performed correctly [42]; however, the lack of knowledge about the water needs of crops can result in inefficient use of water, which in addition to waste can cause damage to the crop [43]. Many citrus growers have adopted irrigation to improve production, but one of the obstacles to increasing efficiency in water use is the lack of information on proper irrigation management [44].

3.3. Seasonality of the Energy Balance

Hourly variations in the radiation balance and the heat fluxes are shown in Figure 5. It is observed that during the night period, all the components of the energy balance are negative ($LE < H < G$), becoming positive as the first solar rays appear and the Rn begins to rise. Such inversion occurred in the period, on average, from 7:00 am during the wettest period (Figure 5a) and from 6:20 am during the less rainy period (Figure 5b).

During the wettest period, the radiation balance reached maximum values around 10:00, with instantaneous peaks of up to 641 W m^{-2} (Figure 5a), while in the less rainy period the instantaneous peaks reached 802 W m^{-2} around 11:00 (Figure 5b). The average reduction of 20% in the hourly values of Rn during the wettest period is due to the increase in cloud cover due to the seasonality of rainfall that occurs in the northeast region of Pará in general, as already evidenced in studies by Farias et al. [45] in Castanhal, Souza et al. [46]

in Salinópolis, and de Sousa et al. [17] in the municipality of Capitão Poço, who observed the irregular distribution of rainfall over the years, directly influencing the variation in the amount of energy that affects the system.

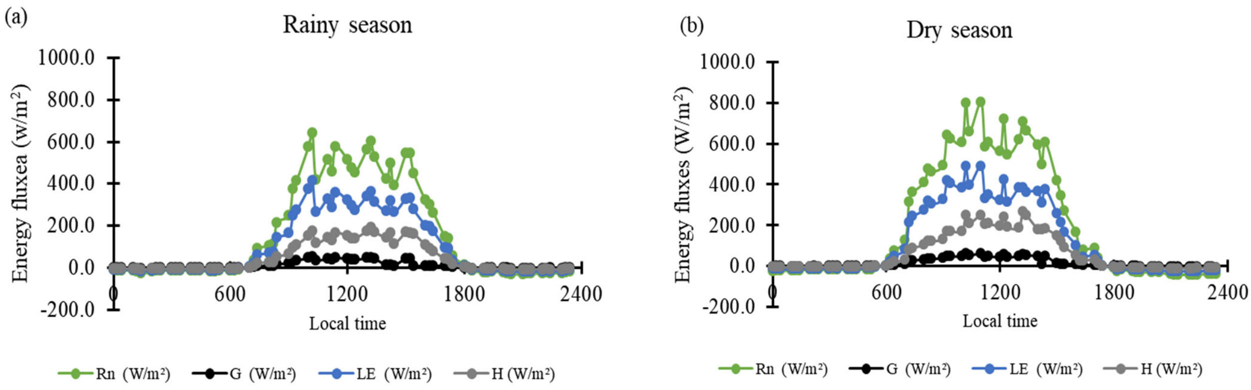

Figure 5. Average hourly variability of the components of the daily energy balance during the wettest period (**a**) and the less rainy period (**b**) in an experiment with Tahiti acid lime in Capitão Poço in PA.

It was verified during the experiment that the latent heat flux presented an average difference of 15% between the periods of greater and lesser rainfall, in the less rainy period it presented an instantaneous peak of 490 W m^{-2}, and in the wettest period the instantaneous peak verified was 415 W m^{-2}.

Although the wettest period presents a greater amount of water available for plants, the lower demand for water from the atmosphere, influenced by the reduction in the values of VPD, Tair, and u2 and the increase in RH, ended up limiting the evapotranspiration power in this period. Connected to this, it is noted that the water supply due to the high water content in the soil at certain times may also have contributed to a greater instantaneous use of energy in the form of *LE* during the less rainy period.

The sensible heat flux (H) showed lower energy values than *LE*, with maximum energy in both periods occurring at 13:40 with 267 W m^{-2} (Figure 5a) during the rainiest period and 290 W m^{-2} (Figure 5b) during the less rainy period. The *H* is influenced not only by solar radiation, but also by the interaction of variables, such as RH, u2, cloudiness, and precipitation. Santos et al. [47] showed a greater amount of use of available energy in the less rainy period due to the reduction in the amount of water available (Figure 4), which caused an increase in the energy used in heating the air.

As for the soil heat flux (G), maximum energy was verified after 14:00 due to the energy being used first to heat the air above the soil surface. Only after that does the soil heat up, causing changes in the value of G. The maximum instantaneous values of *G* observed were 44 W m^{-2} (Figure 5a) and 56 W m^{-2} (Figure 5b) for the most and least rainy periods, respectively.

The high amount of water observed during the experiment directly influenced the values of *H* and *G* when compared to the *LE*, which were relatively lower, confirming, therefore, that most of the energy available in the planting of Tahiti acid lime is predominantly used in the evapotranspiration process. Similar results were observed by Marin et al. [43] in a study of Tahiti acid lime in the city of Piracicaba, where more than 65% of the available energy was used by the flow of latent heat.

Throughout the experiment, it was observed that the energy available in the system is mostly partitioned to the latent heat flux (Table 5), being used in evapotranspiration, with average percentages (LE/Rn) during the wettest and least rainy period corresponding to 63 and 60%, respectively. It can be seen that the slight superiority in the percentage of LE/Rn partition for the wettest period is related to the lower resistance of the canopy to transport water vapor during this period [48], due to its greater water availability and, consequently, greater volumetric water content in the soil, due to the greater rainfall (Figure 4). Greater rainfall is observed mainly in the first months of the year in the region [17], despite having presented instantaneous cases of lower energy in the form of latent heat at certain times. The higher leaf coverage (LAI) observed during the wettest period may also have contributed to the increase in energy consumption in its latent form during the wettest period in percentage terms (Table 5) since the greater the leaf area, the lower the plant's resistance to vapor transport as long as there is a water supply [48].

Table 5. Leaf area index, decoupling factor, daily average of energy balance components, and diurnal partition during the most rainy and least rainy season in the experiment with Tahiti acid lime in Capitão Poço in the state of Pará, Brazil.

Period	IAF	Ω	Energy (MJ m^{-2} d^{-1})				Energy Partition		
			Rn	*LE*	*H*	*G*	*LE/Rn*	*H/Rn*	*G/Rn*
Most Rainy	2.12	0.74	11.84	7.43	3.83	0.63	0.63	0.32	0.05
Least Rainy	1.91	0.81	13.69	8.35	4.65	0.82	0.60	0.34	0.06

The available energy that is partitioned to *H* shows a pattern contrary to the *LE* values during the two evaluated periods, where there were lower percentages during the wettest period and higher percentages during the less rainy period. In the first period (most rainy) where soil water conditions are satisfactory (volumetric soil water content higher than the limit of readily available water), 32% of the available energy was used for daytime heating of the air, while for the following period an increase of 2% was observed.

The *G* showed a pattern of partitioning of available energy similar to H, but of lower magnitude, with a slightly lower percentage in the first period (most rainy) when compared to the following period (least rainy) (Table 5). A possible reason for the increase in *G* values between these periods is that weed control is carried out with heavy machinery primarily during the period with lower rainfall (Figure 4) to avoid drastic changes in physical properties of the soil (such as the global density). This causes greater exposure during the second semester, increasing in this period the incidence of direct radiation to the soil and causing greater heating and an increase in the flow of energy towards the soil.

The energy partition responses for the cultivation of Tahiti acid lime found in this study corroborate the results of research carried out in the northeast region of Pará on the energy balance in perennial crops, such as a study by Souza et al. [49] on a rainfed mango orchard and a study by Sousa et al. [17] on an irrigated açaí plantation. Both studies verified the same seasonal pattern of partitioning of available energy, *LE* > *H* > *G*.

3.4. Evapotranspiration and Crop Coefficient

When converting the diurnal *LE* values into water depth, it was observed that the total water consumption by the Tahiti acid lime during the 15 months evaluated (from 10/2020 to 12/2021) was 1598 mm (Table 6); during the least rainy period, average monthly water consumption was 18% higher than the average during the wettest period. Although there is a greater partition of energy to its latent form during the wettest period, in absolute terms, this energy used in evapotranspiration is higher in the dry period due to the increase in the supply of energy balance.

The difference found between the periods is also a reflection of the variability of atmospheric demand, which is highly influenced by the 77% reduction in total rainfall during the second half of the year (less rainy period) and by meteorological factors that increase water consumption values, such as wind speed, vapor pressure deficit, and temperature increase [50].

Table 6. Monthly variability of rainfall, effective rainfall, water consumption, and daily average of crop evapotranspiration (ET_c) and crop coefficient (Kc) over 15 months of experiment with Tahiti acid lime in Capitão Poço in the state of Pará.

Year	Months	Rainfall (mm)	Effective Rainfall (mm)	Water Consumption (mm)	ET_c (mm d^{-1})			Kc		
					Avg [1]	Max [2]	Min [3]	Avg	Max	Min
2020	October	9	8.9	50	4.2	4.7	3.6	1.2	1.3	1.1
	November	126	100.6	131	4.4	5.3	2.6	1.3	1.6	1.1
	December	6	6	122	3.9	5.1	2.6	1.2	1.4	1.0
2021	January	276	152.6	107	3.5	4.7	1.7	1.2	1.4	1.1
	February	506	175.6	91	3.3	4.8	0.8	1.3	1.4	1.2
	March	320	157	86	2.8	4.3	1.2	1.2	1.3	1.4
	April	276	152.6	104	3.5	4.9	1.1	1.5	1.4	1.4
	May	431	168.1	103	3.3	4.6	1.5	1.5	1.6	1.4
	June	408	165.8	100	3.3	3.9	1.7	1.5	1.6	1.3
	July	237	147.1	106	3.4	4.2	2.6	1.4	1.6	1.3
	August	141	109.2	120	3.9	4.5	1.9	1.4	1.6	1.3
	September	104	86.7	119	4.0	4.5	3.0	1.4	1.5	1.3
	October	99	83.3	126	4.2	5.0	3.3	1.4	1.5	1.3
	November	132	104.1	120	4.0	4.8	2.3	1.3	1.5	1.2
	December	78	68.3	113	3.7	4.7	1.9	1.5	1.6	1.3
Total/Average		3149	1685.9	1598	3.7	4.7	2.1	1.4	1.6	1.2

Note: Average (avg) [1]; Maximum (Max) [2]; Minimum (Min) [3].

These results of the partitioned values of the energy flux used by the Tahiti acid lime support the possibility of adopting seasonal strategies in the region for the crop to attenuate the values of the flows destined for heating of the air and the ground. Considering that rainfall in the Amazon as a whole is concentrated during the first half of the year (Table 6), which directly influences the reduction of volumetric water content in the soil in the following period (Figure 4), lack of knowledge of the real need of water by the citrus crop favors the increase of H and G in this second period of the year. Therefore, measurement and replacement of the total amount of water used by the crop is essential for the latent heat flow to be the main part of the energy available for the evapotranspiration process.

It can be seen that the ET_c values of Tahiti acid lime are lower during the rainiest period (Table 6), despite this period presenting satisfactory soil water conditions for the growth and development of the crop and the LAI having been higher by 10% when compared to the less rainy period (Table 5). This result can be interpreted by the fact that the crop decoupling factor (Ω) presents a value closer to 1 (Table 5) in this wettest period, indicating a condition of decoupling of the vegetated surface with the atmosphere, which means that ET_c no longer responds directly to leaf cover, being influenced mainly by energy availability (solar radiation and Rn). The high decoupling factor (0.81) also obtained during the less rainy period suggests that the greater gas exchange between the atmosphere and the plants was due to the good water condition of the soil (humidity close to the limit of easily available water), lower RH values, and increased VPD, u2, and Tair due to the increase in Rn [36], which in this case was also the main controller of the gas exchange process between the canopy and the atmosphere.

The ET_c variability from 0.8 to 5.3 mm found in this study (Table 6) is close to the results found in the research by Barboza Junior et al. [44] with weighing lysimeter and by Marin et al. [43] with the Bowen ratio method in studies on the water requirement of acid lime in Brazil, where the authors found ET_c ranging from 1.2 to 5.6 mm and from 1.04 to 6.59 mm, respectively. This demonstrates the accuracy of the Bowen ratio method in determining crop evapotranspiration, which has already been proven in several previous studies, such as those by Rana and Katerji [51], Souza et al. [52], and Billesbach and Arkebauer [18].

It is observed that over the 15 months of the experiment, the atmospheric water demand was always lower than the crop water demand (*Kc* > 1), which is related to the fact that the plantation is highly dense and has a larger leaf area when compared to grass, which is the standard crop in the calculation of ET_o. This promotes superior gas exchange rates of Tahiti acid lime, resulting in a greater evapotranspirationable surface.

The *Kc* values found in this study (Table 6) differ from several other studies that aimed to determine the *Kc* for the acid lime crop. Guerra, Grajales, and Rojas [53] found a *Kc* value of 1.0 for the regions of El Espinal and Tolima. In the municipality of Piracicaba, São Paulo, Marin and Angelocci [54] obtained an average *Kc* of 0.65 for summer and 0.24 for winter, while Barboza-Junior et al. [44], who studied acid lime in the same region, found an average *Kc* of 0.98. All authors emphasized that these values provide a useful basis for the design and operation of irrigation systems; however, the variability of the results demonstrates the importance of specific studies for a given location.

The types of management and cultural practices adopted and different methods used to obtain both ET_c and ET_o or to determine the *Kc* itself (single or dual) are factors to be considered and may explain the differences obtained between different regions. The large difference found between the *Kc* values between the studies is mainly related to the climatic conditions of the experiments as well as the characteristics of the study area, such as the planting density (DS) and, consequently, the percentage of soil cover (PCS). Barboza-Junior et al. [44] carried out studies in an area where the DS was 360 plants per hectare with PCS of 69.49%, while in Capitão Poço, the DS was 735 plants per hectare with PCS corresponding to 74.2%.

The differences evidenced between PCS and DS in the studies imply, above all, the greater amount of leaf area available in the Capitão Poço experiment, resulting in higher rates of transpiration, which is the main process of water transfer to the atmosphere [36]. This results in greater demand for water by the crop. The *Kc*, being a coefficient highly influenced by the characteristics of the vegetative canopy and the local climatic conditions, must always be adapted through research for each region in order to increase the efficiency of irrigation management and reduce the overestimates or underestimates that can be generated using *Kc* from other regions.

Studies on water consumption and *Kc* for Tahiti acid lime are still incipient, given the economic importance of the crop for Brazil and for the world. Researchers often face difficulties in installing equipment capable of accurately monitoring the crop's water demand and the atmosphere, in addition to the cost of applying certain methods. As such, the findings of this study are very important to guide water management of the crop in the main citrus pole of the Amazon region. Due to the difficulty of estimating the *Kc* for large areas, one alternative that may be considered is the use of satellite-based ET models for the estimation of the crop's water needs.

4. Conclusions

The partitioning of the available energy in the Tahiti acid lime orchard in the citrus pole of the Eastern Amazon presents reduced seasonal variability when comparing the rainiest periods with the period with low rainfall in the studied region, since on average 61.5% of the energy is used in the evapotranspiration process, 33% is used to heat the air, and 5.5% is used to heat the soil.

The energy balance by the Bowen ratio method is indicated to estimate the water consumption of Tahiti acid lime in the citrus pole of the Eastern Amazon, and in the less rainy period, there are increases of 20% in the average monthly consumption in the wettest period.

The main climatic element that influences the evapotranspiration of the irrigated orchard of Tahiti acid lime in the citrus pole of the Eastern Amazon is solar radiation, while the leaf area index is of secondary importance, given the decoupling of the crop with the atmosphere.

The monthly average of simple crop coefficients (*Kc*) obtained in this study for the Tahiti acid lime is indicated to support irrigation management according to the crop's water needs by farmers, while also allowing for an increase in water use efficiency and rational water use by reducing the waste of water and energy. Additionally, this study may support other research, such as agrometeorological modeling.

Adjustments to the parameters vary with the season and are specific to the growing conditions and planting geometry where the experiment was conducted.

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