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Forest transpiration in Brazilian drylands: measurement and validation of a hydrological model

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ABSTRACT

Transpiration, particularly in dryland forests, plays a major role in the water cycle. The one-million km^2 Caatinga Biome is a data-scarce region in the Brazilian Semiarid, where rainy and dry season are clearly distinct. This work aims to measure the natural Caatinga vegetation transpiration using sap flow monitoring (between Feb 2016 and Dec 2017) and to validate the hydrological Distributed Catchment Scale Model (DiCaSM). Measured transpiration *in situ* was on overall average 0.58 mm.day^{-1} for rainy and transition seasons. There is evidence that sap flow does not provide a good representation of transpiration in dry seasons: sap flow is high, whereas, according to the Literature, actual evapotranspiration is negligible (<0.01 mm.day^{-1}) due to a very low soil water content, and, thus, transpiration should also be negligible. Transpiration estimated by DiCaSM presented a well-defined seasonal variability, with values close to zero during the driest months, in agreement to previous literature. Overall, the findings contribute to better expertise regarding the transpiration rates in a dryland environment and may be used in water resources management contexts, as the transpiration process gives insight into local water use and availability.

1. Introduction

Transpiration plays a key role in the exchange of mass and energy in the soil-water-plant-atmosphere system, so its measurement is important to better understand the role of vegetation in the hydrological cycle. In addition, these measurements supply knowledge about water uses by vegetation in the regions where data are still scarce (Herman et al., 2018; Accioly et al., 2024). The Caatinga Biome, located in the Brazilian Semiarid, is a data-scarce region, whose water availability is highly dependent on rainfall. In such dry regions, it is particularly important to understand plant water use and the transpiration of natural forests (Ungar et al., 2013).

Different methods are applied to measure transpiration, ranging from satellite-based techniques at landscape level to a micrometeorological methodology at catchment level or single plant level (Frank et al., 2015; Novick et al., 2016). The local-scale measurements give insights about the environmental and edaphic factors influencing transpiration. Heat tracer-based sap flow measurement is a group of techniques extensively used to estimate transpiration at the individual plant level due to its accuracy, low cost and ease of installation (Dix and Aubrey, 2021; Wang et al., 2023; Li et al., 2024). Sap flow is an indicator of the plant's physiological performance that allows the integration of soil-atmosphere compartments through a joint structure: an absorbing root system, stem conduction and leaves responsible for gas exchanges (Perez-Harguindeguy et al., 2016; Poyatos et al., 2016).

Various thermometric methods of sap flow measurement were developed and, among them, the thermal dissipation method is the most commonly used (Poyatos et al., 2016). The technique also referred as the thermal dissipation probe method or Granier (1985) method, has been recommended for use in woody species for measuring transpiration (Lu et al., 2004; Poyatos et al., 2016). However, the punctual character of this technique makes it difficult to produce estimates for an entire landscape (Poyatos et al., 2016).

The extrapolation of local data to a larger area is often performed through the modeling of processes. Modeling is crucial for the estimation of transpiration and its partitioning because it provides temporal

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and spatial extrapolation (Senay et al., 2011; Palmer et al., 2020; Santos et al., 2020). Among the available hydrological models, the Distributed Catchment Scale Model (DiCaSM) is a distributed hydrological model (Ragab and Bromley, 2010) that has already been used and validated for runoff generation in the Brazilian semi-arid region (Montenegro, A. & Ragab, 2010; Montenegro, S. & Ragab, 2012). Streamflow and scaled soil moisture (or wetness index) were successfully simulated by DiCaSM in these studies.

Dry regions have distinct ecohydrological processes and this needs to be taken into account in the modeling scheme. This way, in order to develop more accurate hydrological balances, the models need to be validated also considering evapotranspiration fluxes. Models calibrated with real data help to better represent these processes.

Although evapotranspiration had been investigated in the Caatinga Biome before (Pinheiro et al., 2016, 2017; Costa et al., 2021; Vellame et al., 2024), to the authors knowledge, the transpiration portion had never been measured in a multi-year timeline or modeled in a temporal dynamic perspective. Thus, this research is helpful for a better understanding of transpiration in the region. In addition, the validation of models taking into account evaporation processes is even more important because it is a semiarid region, where evapotranspiration patterns are particularly complex.

The present work aims to estimate Caatinga vegetation transpiration by using measured data and to validate a hydrological model on a 12-km^2 forested experimental watershed in the Brazilian drylands.

2. Study area

The focus area of the study is the Aiuaba Experimental Basin (AEB): It is located in northeastern Brazil and comprises an area of approximately 12 km^2 (Fig. 1), whose climate is “Bs” (tropical semi-arid) according to the Köppen classification. The basin is located within a federal conservation unit of the Caatinga Biome and is entirely covered by seasonally dry tropical forest vegetation. The average precipitation is 547 mm year^{-1} concentrated between January and May (Soares et al., 2024). The region’s hydrological regime is characterized by high interannual variability, with a coefficient of variation of 0.40 and 1.20 for annual precipitation and surface runoff, respectively (Güntner and Bronstert, 2004; Medeiros and De Araújo, 2014; De Figueiredo et al., 2016). Potential evaporation averages 2600 mm year^{-1}, measured with a class A tank, and the Penman aridity coefficient is 0.21.

The experimental basin has been monitored since January 2003 (De Araújo and Piedra, 2009; De Figueiredo et al., 2016). Rainfall gauges are used in the AEB (Fig. 1) and record precipitation data every 5 min by a tipping-bucket rain gauge (for information on consistency of the data, see Fullhart et al., 2023). A Time Domain Reflectometry (TDR) sensor, which register soil water content hourly, is installed in the 0–20 cm layer of the soil. The sensor was calibrated to the soil of the area, and more information can be accessed in Costa et al. (2016). In AEB, there are three soil-vegetation associations (SVA, Fig. 1), which are relatively homogeneous units for studies of environmental variables (Pinheiro et al., 2013; De Almeida et al., 2019).

3. Methodological framework

The transpiration assessment workflow adopted six steps, as shown in Fig. 2: i) meteorological data acquisition; ii) plant data collection; iii) transpiration measurement; iv) method validation, v) estimation of transpiration using a hydrological model; vi) statistical analysis to validate the transpiration model.

3.1. Meteorological data

Meteorological data (solar hours, net radiation, air temperature, wind speed, relative humidity; Fig. 3) were obtained from a meteorological station (“EC” in Fig. 1) and information regarding precipitation was obtained from rainfall gauges (“EP” in Fig. 1). We had available meteorological data from 2003 to 2017, so the model was applied for the entire period, with validation specifically conducted for the years 2016–2017.

For the period from 2003 to 2008, sunlight data were provided by the station located in Tauá (approximately 75 km from AEB) (INMET, 2023). From 2009 to 2017, the radiation balance from the EC station at AEB was used instead of sunlight hours. Simulations were performed

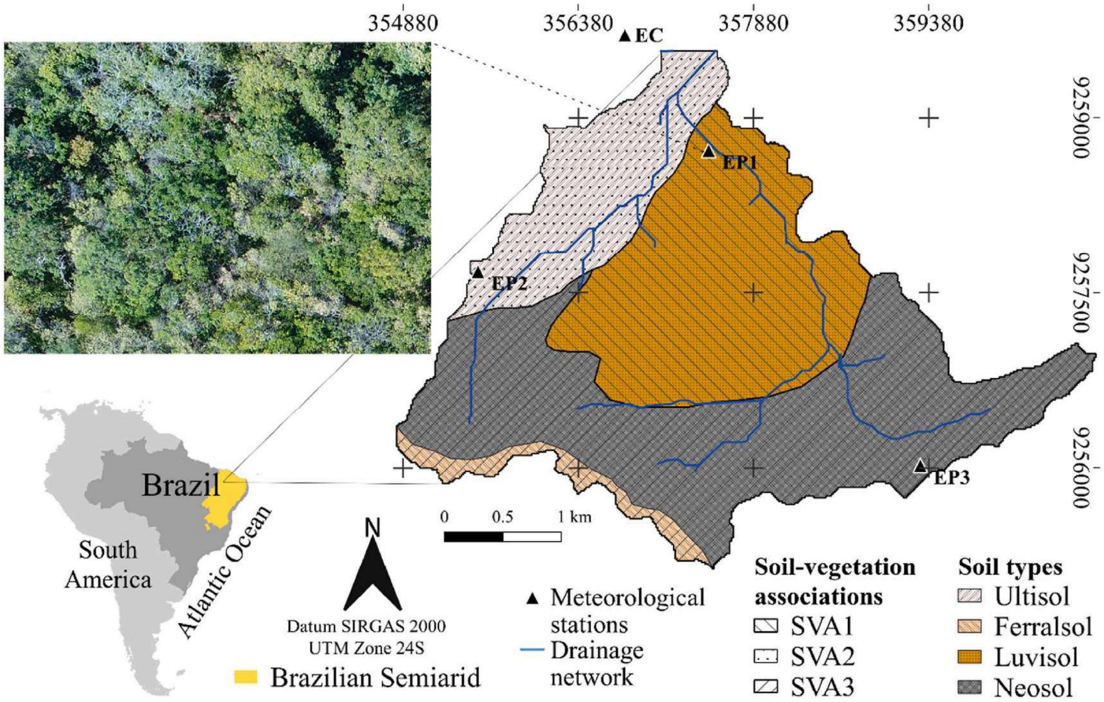

Fig. 1. Location of the Aiuaba Experimental Basin (AEB) with its respective meteorological stations, soils types, and soil-vegetation associations (SVA).

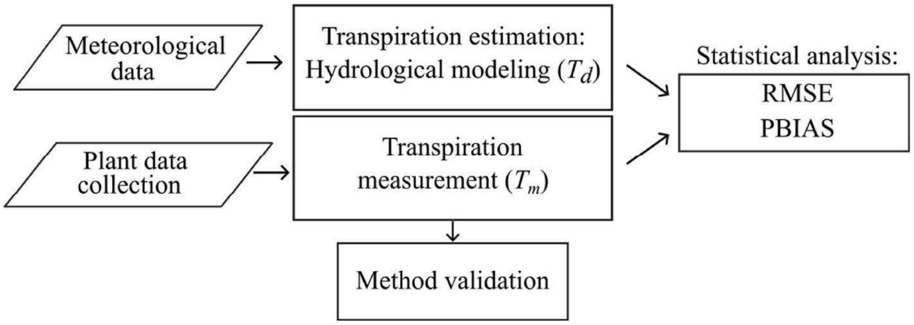

Fig. 2. Flow chart of the methodology used to assess transpiration in the Aiuaba Experimental Basin (AEB).

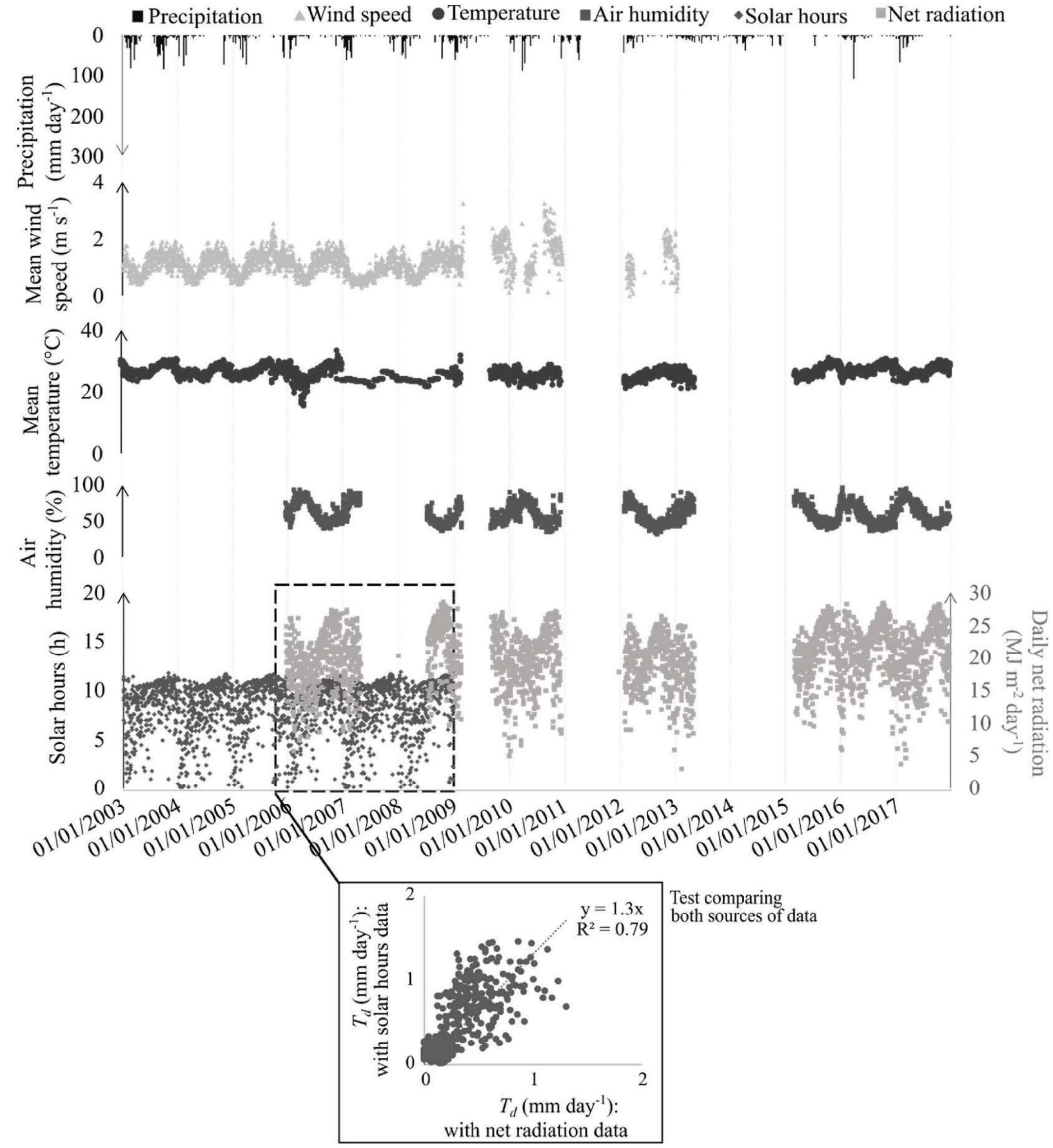

Fig. 3. Daily data from meteorological station (EC) and rainfall gauges (EP) located at the Aiuaba Experimental Basin (AEB).

with the two data sources to verify their equivalence. They proved to be highly correlated for transpiration (T_d) and analogous at a significance level of 5 % by the analysis of variance as shown in the highlight of Fig. 3.

3.2. Plant data collection

The method was applied to plants of the species *Poincianella pyramidalis* (Tul), which are representative of the Caatinga Biome according to Pinheiro et al. (2013), De Almeida et al. (2019), Costa et al. (2023), and Vellame et al. (2024). As observed in the detail in Fig. 1, the vegetation characteristics of Caatinga Biome demonstrate a consistent homogeneity. Most of the vegetation species are herbaceous, and the tree species most common is *Poincianella pyramidalis* (Tul). Some relevant plant data was previously collected to be used in our methodology, as presented in the flowchart in Fig. 2. The plants used in this study had heights of 5.0 m and 8.0 m, canopy projection areas of 12.5 m^2 and 33.2 m^2, and diameter at breast height of 0.09 m and 0.15 m. The hydroactive xylem area was estimated with an allometric relationship derived from wood slices of *Poincianella pyramidalis* plants from the experimental site. The equation that best described the relationship between hydroactive xylem area and diameter at breast height (*D*) was Eq. (3) ($R^2 = 0.98$, $p < 0.05$) and the data used are shown in Fig. 4.

$$A_x = 2.30\ D^{1.76} \qquad \text{Eq. 1}$$

3.3. Transpiration measurements

The transpiration measurements consisted of the sap flow in the hydroactive xylem using a thermal dissipation probe as in Granier (1985). Monitoring happened continuously from February 2016 to December 2017. On 37 % of the days the data were missing or incomplete, on 438 days they were complete and consistent.

The sap flow measurement device consists of two probes measuring 2 mm in diameter and 10 mm in length, which were inserted into the xylem of the trees at a vertical distance of 10 cm (Granier, 1987; Lu et al., 2004). The probes contained a copper-constantan thermocouple in the centre of a hypodermic needle. In addition to the thermocouple, the upper probe has an electrical resistance, fed by an adjustable source that in this research adopted a constant power of 0.2 W, in agreement with Sun et al. (2012) and Ouyang et al. (2018). The sensors were homebuilt and similar material has been used by Costa et al. (2023) and Araújo (2022). No specific accuracy or uncertainty analysis was performed, but comparison with stem moisture and evapotranspiration has proven the sensors' capacity to monitor the process. The sensors were installed 1 m from the ground surface to avoid heat conduction to the ground. We used a CR800 datalogger to heat the sensors and collect probe outputs. The temperature difference between the probes was recorded at 60 s intervals and stored as 60-min averages. The daily value of sap flow was the sum of all the hourly measurements (Eq. (1)).

$$F = \sum 119\left(\frac{\Delta T_{max} - \Delta T}{\Delta T}\right)^{1.231} Ax \qquad \text{Eq. 2}$$

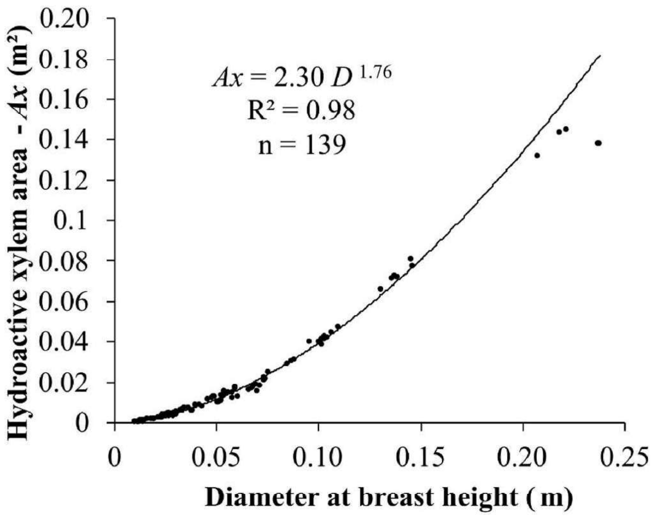

Fig. 4. Relationship between diameter ate breast height (*D*) and hydroactive xylem area (*Ax*) for *Poincianella pyramidalis* (Tul.) plants from the study site.

Where F = sap flow, in L.day^{-1}, ΔT = temperature difference between the two probes, in °C, and Ax is the hydroactive xylem area, in m^2. ΔT_{max} is the maximum temperature difference observed daily, which usually occurs at predawn. In order to escalate the point measurement to the whole plant as daily measured sap flow transpiration (q_{sf}) (Eq. (2)), daily sap flow was divided by projected canopy area (Gubareva et al., 2023).

$$q_{sf} = \frac{F}{CPA} \qquad \text{Eq. 3}$$

Where: q_{sf} = measured sap flux transpiration, in mm.day^{-1}; F = sap flow, in L.day^{-1}; CPA = canopy projection area, in m^2.

3.3.1. Method validation

Transpiration data for forested areas in the Caatinga are scarce. Therefore, to validate the method and the Granier coefficients presented in Eq. (1), we compared its results with two independent datasets of measurements performed at the same site: soil water balance and actual evapotranspiration. Vellame et al. (2024) estimated actual evapotranspiration based on measured data and energy balance. Although transpiration, soil water depletion and actual evapotranspiration are different processes, soil water depletion and actual evapotranspiration are acceptable proxies of transpiration. Vellame et al. (2024) used water balance in the soil to validate their methods to estimate actual evapotranspiration ($R^2 = 0.99$). Also in the same experimental area, Pinheiro et al. (2016) estimated annual actual evapotranspiration using the SWAP (Soil Water Atmosphere Plant) model and validated their findings with daily soil water content measurements.

The variation in soil water content was measured with the data from TDR sensor installed in the area. The data represent the soil layer of 0–0.20 m, not covering the total effective rooting depth (approximately 0.70 m in the area, according to Pinheiro et al., 2013). However, deep drainage at the experimental site has been shown to be negligible (Costa et al., 2013). More information about the sensors and the conversion to volumetric soil water content can be accessed in Costa et al. (2016).

We used the daily average soil water content ($\overline{\theta}_{day}$) to calculate the variation in soil water storage (Δh, mm) for the 0–0.20 m depth of the soil layer (z = 0.20 m), as shown in Eq. (4). We used the daily time interval and the accumulated variation over time. Thus, as pointed out by Vellame et al. (2024), while Δh does not directly represent transpiration or actual evapotranspiration, it is closely related to them, as no deep drainage takes place, especially during the dry season when the soil water content is significantly lower than the field capacity. The accumulated series were compared using the Engle–Granger cointegration test, which can deal with non-stationary time series and still account for their relationship (Seung-Hoon, 2007; Zhang et al., 2015, 2017).

$$\Delta h = z\left(\overline{\theta}_{day} - \overline{\theta}_{day-1}\right) \qquad \text{Eq. 4}$$

3.4. Transpiration estimation: hydrological modeling

DiCaSM (Distributed Catchment Scale Model) is a physically-based distributed hydrological model that was created as an integrated water management strategy to consider climate and land use changes in the hydrological processes of a watershed (CEH, 2019; Ragab and Bromley, 2010). In order to simulate evapotranspiration processes the DiCaSM model version 3.2 (2016) was used, and it was carried out with a spatial discretization of AEB in cells of 500 m × 500 m, totaling 48 cells (Fig. 5).

DiCaSM uses the Raupach (1995) method to calculate potential evapotranspiration for a cell, which may contain a mixture of different land-use types (Ragab and Bromley, 2010). Using soil layer lumping, the model considers the characteristics of all soil types and their layers. Model transpiration output is the difference between actual evapotranspiration and interception losses (CEH, 2019).

Data spatialization of soil types, land use and elevation were carried

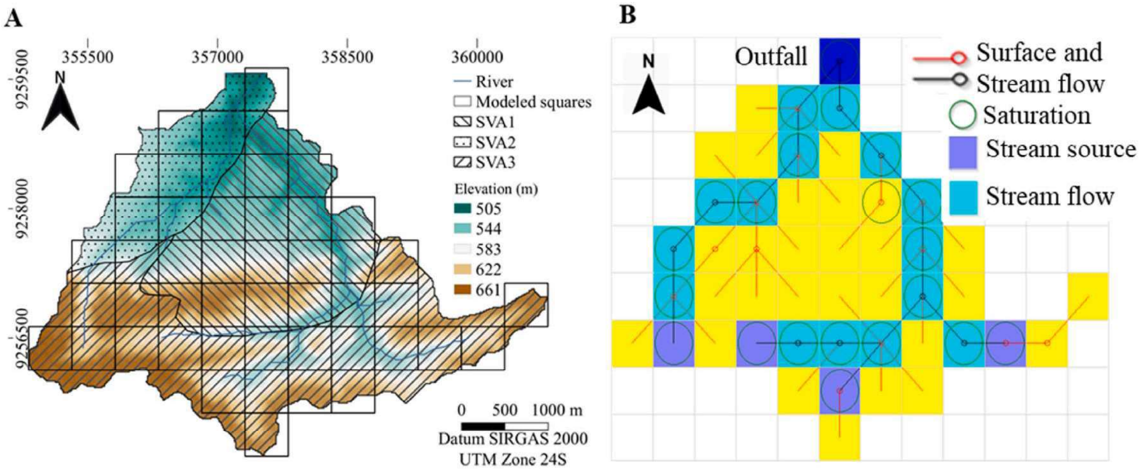

Fig. 5. Discretization of the Aiuaba Experimental Basin (AEB) with 500 m × 500 m cells to apply DiCaSM. (A) Elevation data and SVA distribution; (B) Modeled stream flow map and flow direction. Yellow squares in (B) represent the other modeled cells. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

out (Fig. 5A), and elevation data were used by the model for flow mapping (Fig. 5B). The initial flow depth of the rivers is defined according to the soil layers. As the rivers in the basin are ephemeral, their initial flow depth was considered zero throughout the course. For modeling purposes, a representative tree species was chosen for each SVA: *Poincianella pyramidalis* (Tul.); *Piptadenia obliqua* (Pers.); *Mimosa tenuiflora* (Willd.) (Fig. 1). Since the model considers the annual cycle of deciduous plants, albedo, leaf-area index (LAI) and plant height vary seasonally. Vegetation data were obtained from the following sources: albedo (Pinheiro et al., 2010); effective root depth (Pinheiro et al., 2013); maximum leaf area index and maximum plant height (De Almeida et al., 2019). Pinheiro et al. (2013) and De Almeida et al. (2019) performed *in situ* experiments in different areas of the AEB, considering each SVA. Their data was used according to the different SVA. Canopy

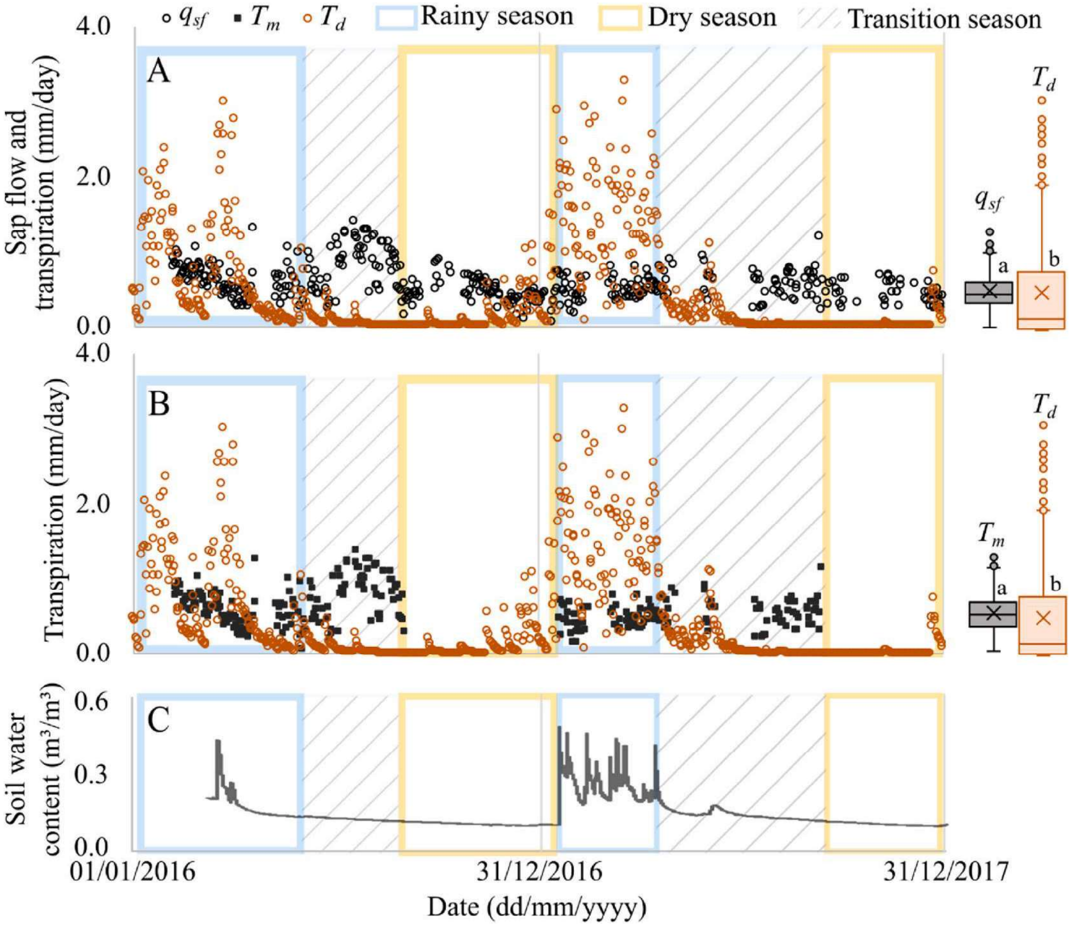

Fig. 6. Transpiration rates obtained from sap flow measurements (q_{sf}) and measured transpiration (T_m, that is dry season sap flow measurements were not considered). Modeled dataset by the hydrological model: DiCaSM (T_d). Groups with the same letters do not differ statistically (Tukey p-value <0.05).

resistance data were standardized and used based on research also carried out in the Brazilian semi-arid region (Teixeira et al., 2008) in which specific values were obtained for rainy (360 s m^{-1}) and dry (2250 s m^{-1}) seasons.

3.5. Statistical analysis

Transpiration values were compared on coinciding dates with modeled data; the metrics used for this purpose were the root mean square error (RMSE) and the percent bias (PBIAS). Furthermore, a one-way ANOVA and a Tukey's honestly significant difference (HSD) test were used to compare the results.

We considered the partitioning of hydrological seasons as described in Soares et al. (2024). According to these authors, the hydrological year can be split into a rainy and a dry season, interconnected by transition seasons. For simplification purposes, we considered here both transition seasons as simply "transition". Temporal evaluation was conducted based on all available data during the period from 2003 to 2017, since it was the period with available data in the area.

4. Results and discussion

4.1. Transpiration measurement: method validation

The temporal distribution of daily sap flow measurements in AEB is shown in Fig. 6A. During the measurement period, sap flow varied between 0.06 and 1.39 $mm.day^{-1}$. Measured sap flow values varied seasonally, and the temporal dynamic of atmospheric demand and soil moisture explains the higher values for the transitions. During the rainy season, soil water content is high, and LAI is also high. However, since atmospheric demand is relatively low, transpiration is restricted. During the dry season, the opposite happens: atmospheric demand is higher, but at the same time restricted by a limited soil water content and reduced LAI. During the transition periods, multiple events happen: high atmospheric demand occurs simultaneously with moderate LAI and soil water content, leading to transpiration rates that might be higher than in the wet season.

The analysis shown in Fig. 6B was performed because similar measured sap flow for the rainy and dry seasons is not in correspondence with previous studies (Marques et al., 2020). Since transpiration is a partition of evapotranspiration, we use a study of actual evapotranspiration as an example of this lack of alignment. Vellame et al. (2024) measured actual evapotranspiration in Caatinga (same study area, AEB) in 2021 and it averaged 5.5 $mm.day^{-1}$ during the rainy season. The measured sap flow averaged 0.54 $mm.day^{-1}$ for the rainy season, corresponding to 10 % of the actual evapotranspiration. However, during the dry season, values close to zero were observed for actual evapotranspiration (<0.01 $mm.day^{-1}$). This behavior differs from our measured sap flow data: sap flow was on average 0.44 $mm.day^{-1}$, which is high compared to the negligible actual evapotranspiration.

Because of this lack of correspondence with literature, we chose to validate the sap flow method using both the measured sap flow (q_{sf}) and transpiration (T_m) data and the water depletion in the soil (Fig. 7). For T_m, we did not consider any sap flow values measured during the dry season. In Fig. 7, we plot the accumulated values for q_{sf} and T_m, together with the accumulated water depletion in the soil over time. We also see two plateaus during the dry seasons when soil water content (Δh) decreases very slowly, while sap flow (q_{sf}) continues happening (also shown over time in Fig. 6C). However, when we eliminated the dry season values (T_m data), we see that the time series started to look like that from soil water content because we create periods with no change. Even so we observe shorter plateaus in T_m, maybe signaling that plant water uptake stopped even before the start of the dry season. These observations were confirmed by the cointegration tests performed for both q_{sf} versus Δh and T_m versus Δh. For qsf, the test results confirmed that the series are cointegrated with a significance level of 10 %. While for T_m, we can confirm the relationship with a significance level of 1 %.

Other studies have observed that the soil water content in the Caatinga reaches limiting levels during the driest months. For instance, Costa et al. (2016) observed that soil water content falls below the permanent wilting point (−1.5 MPa) during the nine driest months of the year. Although Costa et al. (2023) showed that Caatinga plants can survive when the soil water content is below the level commonly determined as permanent wilting point, Pinheiro et al. (2016) demonstrated with simulated data that root water uptake ceases in the beginning of the dry season and restarts, in near-average years, after the first precipitation event.

With the evidence of previous measurements, we understand that sap flow does not correspond to transpiration in the dry season in the Brazilian semiarid region. The water movement that occurs during the dry season can be explained by the water redistribution in the plant caused by the drying of the stem. Costa et al. (2023), observing the temporal dynamic of stem and soil water content in Caatinga, demonstrated that the stem starts to dry out at a higher rate when soil water content is below the permanent wilting point and keeps drying until it reaches a minimum value and stabilizes.

Some other reasons for the overestimation of transpiration could be linked to the measurement method itself. In the literature, some of the limitations of the method are known. First, there are various factors related to probe insertion, such as wound size and depth, influence the accuracy of sap flow data (Wiedemann et al., 2016; Wullschleger et al., 2011). Secondly, the errors caused by azimuthal and radial variations of sap flow density can lead to misinterpretation of sap flow (Clearwater et al., 1999; Cohen et al., 2008; Bush et al., 2010; Shinohara et al., 2013;

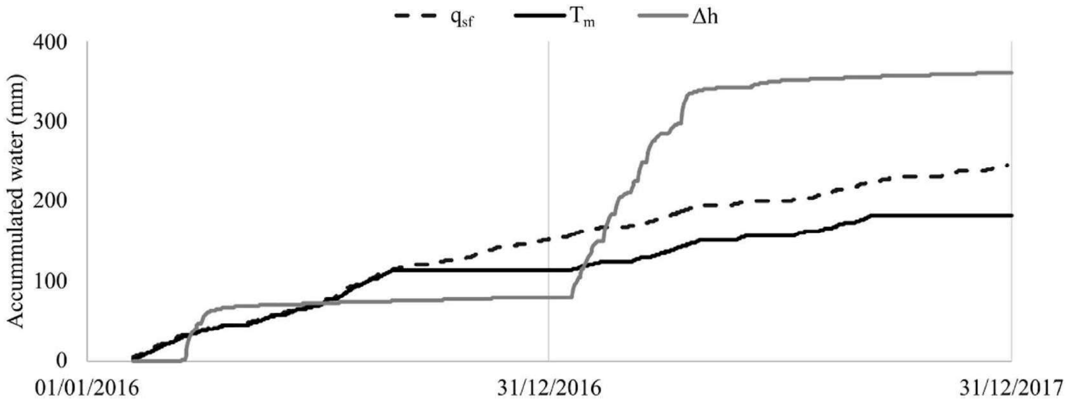

Fig. 7. Accumulated sap flow data (q_{sf}), daily transpiration (T_m, that is dry season sap flow measurements were not considered) and soil water depletion from the surface layer (0–0.20 m) during the monitoring period: February 2016 to December 2017 (n = 667).

Molina et al., 2016). Sap flow density varies across different azimuthal and radial profiles, as well as can be influenced by the methods for estimating sapwood area (Molina et al., 2016).

There may be causes of water movement in the plant other than transpiration. Usually, it is considered that water moves from the soil, through a plant, and to the atmosphere in the form of vegetation leaf transpiration. However, there may be other paths, as per Goldsmith (2013), who stated that plants can absorb water from the atmosphere. Foliar water uptake occurs in nearly all biomes and Berry et al. (2019) reviewed this process focusing on the plant and the atmospheric water potentials that are necessary to create a water flow gradient. Yet it is still unknown what effect this process has on overall plant water uptake and balance. In addition, night transpiration is frequently disregarded as there is no radiation, but it can be relevant as observed by other authors (Alvarado-Barrientos et al., 2015).

Table 1 presents the summary of our results. With the support of previous literature and the comparison of the measured soil moisture averaged in each season (Fig. 6C), we considered that sap flow measurements are equivalent to transpiration in rainy and transition seasons (Fig. 6B). In dry seasons, on the other hand, transpiration was not considered valid. Looking into the soil moisture data, we observe that this occurs when measured soil moisture averages in the range of the permanent wilting point of the superficial soil layer, in agreement with Costa et al. (2013). This assumption is also supported by the experimental evaluation of Vellame et al. (2024), Costa et al. (2016) and Pinheiro et al. (2016) in the same experimental basin, when these authors measured actual evapotranspiration.

If we consider that all days with measured values in the dry season were equal to 0.01 $mm.day^{-1}$ (as in Vellame et al., 2024), the overall annual weighted average was 0.42 $mm.day^{-1}$. Taking into consideration the average annual precipitation in the region (547 mm), this transpiration would represent 28 % of the total precipitation. Pinheiro et al. (2016) studied AEB through hydrological simulations in SWAP (Soil Water Atmosphere Plant) and calculated an average transpiration of 0.50 $mm.day^{-1}$, which represents 33 % of the average annual precipitation and shows that the values in both investigations are of the same order of magnitude.

Caatinga vegetation possesses multiple morpho-anatomical evolutionary adaptive traits to cope with water deficit and high temperatures, as observed by Accioly et al. (2024). These characteristics include the presence of structures, such as thick cuticles, trichomes and crystals. The configuration of some traits is also commonly observed to maximize plant tolerance to harsh natural conditions. Among the adaptation mechanisms is the stomatal closure, which occurs in the hottest period of the day/year and is a plant response to the onset of drought conditions (Santos et al., 2014). Silva et al. (2008) observed that this natural mechanism is a manner of surviving the dry season, since it allows the regulation of the water potential inside the leaves.

In the Caatinga environment, soil water content is lower than the permanent wilting point on average nine months per year, which affects water absorption and consequently transpiration (Costa et al., 2016). Hence, Caatinga vegetation is characterized by low water uptake during the dry season because of its physiological and morphological adaptations and the low availability of water during this period.

Furthermore, the vapor pressure deficit generated by transpiration is extremely reduced during the dry season due to leaf area loss, and this fact attenuates the effect of wind speed on transpiration rates. The leafless canopy can decrease aerodynamic resistance by enhancing airflow and vapor removal. However, under water stress conditions, plants tend to increase canopy resistance to avoid losing water, so transpiration is restricted even when radiation is high (Teixeira et al., 2008). During the dry season the evapotranspiration processes are source-limited, that is to say that there is no water available to be used by the plant (Vellame et al., 2024).

4.2. *Model validation*

Fig. 6 presents estimated transpiration over time for the period of measured data. We observe in the graph that the model presents a distinct seasonality, with DiCaSM simulating transpiration with values close to zero during the dry season, in agreement with previous studies at AEB (Costa et al., 2016; Pinheiro et al., 2016; Vellame et al., 2024).

A statistically significant difference between all groups was observed in the sap flow measurements, as determined by ANOVA followed by Tukey's post-hoc test (Fig. 6A and B). Since we did not attribute any data for the dry season measurements, we could not validate the DiCaSM model for transpiration estimation, even though its output aligns with values reported in the literature.

For the rainy season, the modeled values for transpiration were on average close to measured transpiration, with an error of 0.97 $mm.day^{-1}$ (RMSE). However, the bias of DiCaSM transpiration was +114 % (PBIAS) for the rainy season. During the transition season, the model presented lower errors (0.73 $mm.day^{-1}$) and smaller bias. DiCaSM underestimated measured transpiration with a bias of −67 %. Some morphoanatomical traits of Caatinga vegetation might be restricting transpiration during the rainy season for the models in an unexpected way.

Overall, DiCaSM seems to have captured the temporal dynamics of what transpiration in Caatinga is like, particularly during the dry season with very low values (in agreement with literature-based expectations). For transition seasons smaller errors were observed with estimation errors equivalent to average measured transpiration. Suitable estimations of transpiration are important as often estimations neglect this specific fraction of water uptake through vegetation to the atmosphere, considering evapotranspiration as a whole output (Singer et al., 2010). The results also help to understand transpiration rates in this data-scarce semiarid region. However, we acknowledge that the spatial analysis of the model output was not performed, and this might bring other insights into the analysis.

4.3. *Temporal analysis*

Fig. 8 displays the estimated transpiration rates (T_d) over time and the seasonality between January 2003 and December 2015. Some missing data in the meteorological station during the study period (Fig. 3) led to gaps in T_d, since DiCaSM demands meteorological data.

Overall, no trend was observed in transpiration over the modeling period. However, only 13 years were examined and this period

Table 1

Daily average values in $mm.day^{-1}$ in different seasons for sap flow measurements (q_{sf}), measured transpiration (T_m, that is dry season sap flow measurements were not considered) and estimated transpiration using DiCaSM (T_d). The symbols represent: *Ndays* = number of days with measured data in each season; *SWC* = soil water content ($m^3.m^{-3}$).

Season (Ndays)	SWC	q_{sf}	T_m	T_d	RMSE	PBIAS
Rainy (155)	0.23	0.54	0.54	1.04	0.97	+114 %
Transition (140)	0.14	0.68	0.68	0.15	0.73	−67 %
Dry (143)	0.11	0.44	[a]	0.10		
Annual (438)	0.15	0.56		0.38		

[a] Assumption that this data is not valid for the dry season based on data measured by Vellame et al. (2024), Costa et al. (2016) and Pinheiro et al. (2016).

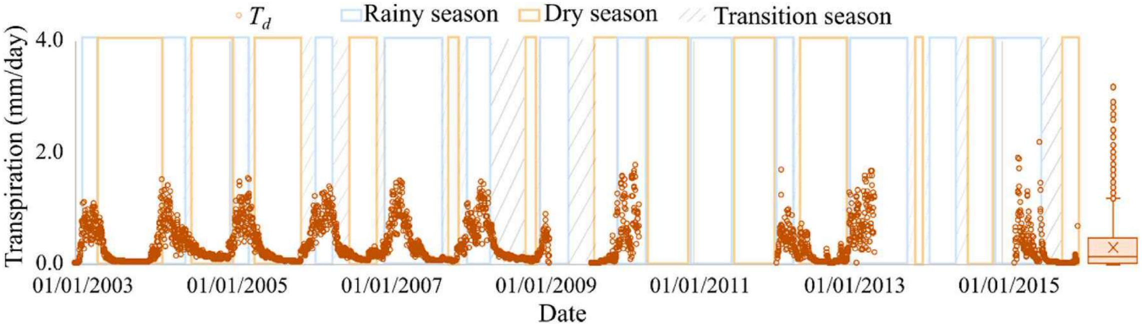

Fig. 8. Transpiration rates obtained with modeling using DiCaSM (T_d). The partitioning of hydrological seasons was done as described in Soares et al. (2024).

encompassed the impacts of a drought that started in 2012 (Azevedo et al., 2018; Marengo et al., 2020). Other authors suggested that the warming climate is leading to an increasing temporal evapotranspiration trend in Caatinga, as reported by Costa et al. (2021). They showed a positive trend in the air temperature of 1.5 °C, and 2.2 mm per year in actual evapotranspiration. If we consider 41 % of evapotranspiration as transpiration (as per Pinheiro et al., 2016), the positive trend of vegetation transpiration is 50 mm in 55 years. In the semiarid Pinares Forest of Spain (Valladolid, Spanish Northern Plateau), Costa et al. (2021) also observed a positive evapotranspiration trend of 3.9 mm year^{-1}. This positive (or increase) trend in actual evapotranspiration is an indication that Brazilian society should evaluate other semiarid environments in the globe so as to adapt to the consequences of increasing (evapo) transpiration for biodiversity and water availability.

The Caatinga is an essential biome as it provides crucial ecosystem services, such as, amortizing evaporation at the reservoir margin (Koh et al., 2010; Guenther et al., 2012; Rodrigues et al., 2021), impacting lake recharge (Hallema et al., 2018), improving water quality (De Mello et al., 2017), as well as reducing soil erosion (Medeiros et al., 2009). Therefore, an understanding of transpiration rates and how they vary over the watershed is critical for good water balance management, essentially in water-scarce regions such as the Caatinga Biome. The results reinforce the potential for the application of hydrological modeling to accurately investigate hydrological processes in data- and water-scarce regions.

5. Conclusions

In this study transpiration rates were evaluated during the rainy, dry and transition seasons of 2003–2017 in the Aiuaba Experimental Basin, located inside a Caatinga preservation area in the semiarid region of Brazil. Measured transpiration *in situ* was on average 0.58 mm.day^{-1} for rainy and transition seasons, with higher values in the transition season. Sap flow measurements during the dry season were not in agreement with previous studies in Caatinga: Measurements showed dry season sap flow to be as high as during the rainy season, whereas actual evapotranspiration was previously proved to be negligible in that season. This indicates that, during the long dry season in the Caatinga, sap flow depicts water movement in the plant due to moisture redistribution, rather than due to transpiration.

DiCaSM presented a seasonal behavior closer to what was expected for transpiration in Caatinga with values close to zero during the dry season. The errors and bias observed for the rainy and transition seasons can be explained by the fact that Caatinga vegetation has mechanisms to avoid extra losses of water to the atmosphere, and the model may not be adequately accounting for this specificity. Overall, the modeling approach presented smaller errors for the transition seasons.

Transpirations estimation during the dry season was a challenge for *in situ* measurement and that is why it was difficult to be evaluated through modeling. We did not conduct a formal uncertainty analysis for the sap flow sensor and this lack of validation is acknowledged as a limitation of our study. A better assessment of precise transpiration measurement for dry seasons is necessary in order to better apply the methodologies. Although we answered some questions regarding transpiration rates in a semiarid watershed, further research is needed. A comparison between sap flow and eddy covariance transpiration measurement would be ideal, especially to understand the seasonality of water flux dynamics. On top of that, it would be beneficial for future modeling applications to have multiple transpiration measurement points in a watershed to make a spatialized calibration of the transpiration processes and gain a more detailed understanding. Overall, the findings contribute to better expertise regarding the transpiration rates in a dryland environment and may be used in water resources management contexts, as the transpiration process gives insight into local water use and availability.

CRediT authorship contribution statement

Nazaré Suziane Soares: Writing – review & editing, Writing – original draft, Formal analysis, Data curation. **José Vidal de Figueiredo:** Writing – review & editing, Writing – original draft, Investigation, Conceptualization. **Carlos Alexandre Gomes Costa:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Italo Sampaio Rodrigues:** Writing – review & editing, Writing – original draft, Formal analysis, Data curation. **José Carlos de Araújo:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Jose Carlos de Araujo reports financial support was provided by Coordination of Higher Education Personnel Improvement. Nazare Suziane Soares reports financial support was provided by Coordination of Higher Education Personnel Improvement. Nazare Suziane Soares reports financial support was provided by Foundation for Scientific and Technological Development and Support of Ceará. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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