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Relationship between trunk diameter fluctuations and physiological variables in adult cocoa trees

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It is important to know the water status of cocoa plants because a water deficit negatively affects fruit set and fruit maturity reducing their quality. The objective of this work is determining the existence of a relationship between the fluctuation of trunk diameter and the water status of adult cocoa trees which will allow a continuous and low-cost measurement of the water status of the plants. To meet this objective a trial was carried out at Hacienda La Clemencia located in the province of Guayas- Ecuador, the foliar and stem water potentials, maximum daily trunk fluctuations (MCDT), gas exchange, and soil moisture levels were evaluated. The trial was conducted for 128 days, from July to October 2023. The physiological variables were measured twice a week, while the meteorological variables, soil moisture, and MCDT were recorded continuously. The results showed that there is a correlation between the physiological variables evaluated and MCDT. In conclusion, there is a significant relationship between stem potential and MCDT in adult cocoa plants.

KEYWORDS

maximum daily trunk fluctuations, reference crop evapotranspiration, irrigation, soil moisture, water potential

1 Introduction

Cocoa (*Theobroma cacao* L.) is a perennial crop of great economic importance for exporting countries in the Americas, Africa, and Asia (Nair, 2021). In Ecuador, cocoa plantations occupy more than 12% of the total cultivated land, generating direct jobs for about 4% of the working population (Neira, 2016).

Despite the importance of cocoa cultivation as a significant source of income for millions of small farmers, much is yet to be explored regarding the functioning of the cocoa tree. This can be explained since experimental work is costly and time-consuming, and it has a long production cycle, resulting in little knowledge about the plant's response to water stress conditions, climate change, nutrient effects, and phenology. At present, no tools are available to support decision-making regarding its main agricultural practices, such as irrigation, fertilization, and pruning (Tosto et al., 2023).

It is estimated that in Latin American countries the irrigation needs of perennial crops will increase due to climate change, affecting water availability in the coming decades because of the increasing crop requirements (Borja et al., 2017).

A study by Ortiz-Bobea et al. (2021), states that since 1961 there has been a reduction in agricultural productivity by ~26-34% due to the effect of anthropogenic climate change (ACC) in warmer regions such as Africa, Latin America, and the Caribbean.

Cocoa farmers in Ecuador unfortunately, are poorly prepared to adopt techniques to cope with changes in rainfall patterns because of climate change (Idawati et al., 2024). Consequently, it will be essential to use technology to improve irrigation efficiency and adopt agricultural practices that lead to a sustainable model for cocoa production (Moreno-Miranda et al., 2020).

The adoption of irrigation technologies can reduce the impact of climate change on crop production. These technologies can reduce the impact on yields due to the effect of strong climatic variability, characterized by high temperatures, reduced rainfall and shorter rainy seasons (Cavazza et al., 2018).

In cocoa plants, water shortage in the soil causes morphological (reduced root development, foliar, plant vigor), physiological (reduced photosynthetic activity, stomatal density, chlorophyll, water potential), biochemical (reduced superoxide dismutase, catalase, ascorbate peroxidase, increased ethylene), and chemical (reduced macro- and microelements) problems (Janani et al., 2019; Alban et al., 2015).

In crops such as grapes has been evidence is available that there is a strong correlation between soil water potential, plant water potential, and stomatal conductance (Centeno et al., 2010). Water potential is the most commonly used parameter to indicate the plant water status and determine irrigation timing in grapes (Barbagallo et al., 2021). However, it is a difficult measure to take, as it requires equipment and specialized labor.

The water potential is a point measurement, necessitating a dynamic nature indicator for developing irrigation programs that account for climatic and soil conditions. There are experiences in peach and lemon trees that continuous and automatic data can be obtained by measuring trunk diameter fluctuations, allowing the immediate detection of water deficit situations (Goldhamer et al., 1999; Ortuño et al., 2009).

Currently, there is a boom in the development of new techniques to evaluate plant water status directly, continuously and in real time, such as sap flow (SF) and Maximum daily trunk shrinkage (MDS), which have been successfully used in different crops (Ortuño et al., 2006b; Conejero et al., 2007; Mirás-Avalos et al., 2016; Chai et al., 2021; Zhao et al., 2023). These advancements aim to improve irrigation management, enhance water use efficiency, and produce higher-quality food with lower environmental impact (Velasco-Muñoz et al., 2019).

Given this context, it is necessary to optimize water use by adopting irrigation technologies that mitigate the impact of ACC on crop production. These technologies can reduce the reliance of crop yields on rainfall distribution, which is often associated with unpredictable variability (Cavazza et al., 2018; Velasco-Muñoz et al., 2019).

In this regard, advances have been made using parameters derived from micrometric variations in trunk diameter (very small variations that occur in stem diameter) what serve as indicators of plant water status. These methods have been tested in various perennial crops, including peach (Conejero et al., 2010; Mirás-Avalos et al., 2017), grape (Zhang et al., 2021), lemon tree (García-Orellana et al., 2007), olive tree (Moriana et al., 2011; Girón et al., 2016), almond tree (Puerto et al., 2013), and plum trees (Paltineanu et al., 2020).

Although this technique has been known for more than twenty years, there are few studies of this type in tropical conditions. Studies of this type in tropical conditions are few. The greatest benefit of this technique is could that it replaces traditional soil water status measurements, which are time-consuming, costly, and require specialized labor

Based on the above, the objective of this study is to determine the relationship between trunk diameter fluctuation and the plant water status of adult cocoa trees by (1) evaluating the behavior of physiological variables of adult cocoa trees, (2) correlating physiological variables with meteorological parameters, and (3) correlating water potential (leaf and stem) with MCDT.

2 Materials and methods

The trial was conducted at Hacienda "La Clemencia", located in Canton Balzar, in the southern part of Guayas Province (1°9'59.24" S and 79°44'23.13.13" W), at an altitude of 63 meters above sea level. The region has a dry tropical climate (Köppen climate classification: Aw). The study utilized 22-year-old cocoa trees (*Theobroma cacao* L.) of the CCN-51 genetic material, full production, well maintained, planted in full sun and at a spacing of 1.8 x 2.70 m with 3.80 m between rows. CCN 51 was a clone developed in Ecuador through crosses of ICS-95×IMC-67 (International Cocoa Germplasm Database, 2006).

Within the study plot, two test pits were excavated, where the Ap, A1, B1, and B2 horizons were found, with textural variability ranging from silt loam to clayey soil, characterized by angular and subangular block structures. Roots were observed to a depth of 87 cm, and undeformed soil samples were taken using 100 cm^3 cylindrical rings using an Uhland auger in each horizon. These samples were then transported to the laboratory of the Department of Soil and Water Management (DMSA) at the Pichilingue Tropical Experiment Station (EETP) for soil density and hydraulic conductivity determination. The Ap horizon showed average hydraulic conductivity values of 4.8 and 2.9 cm h^{-1}. Hydraulic conductivity decreased with depth, reaching 1.2 cm h^{-1} in the B2 horizon.

Soil pH across different horizons ranged from 5.5 to 6.3, which did not pose any issues for crop nutrition. Nitrogen (N), phosphorus (P), sulfur (S), and boron (B) levels decreased with soil depth. In general, the availability of bases such as calcium (Ca), magnesium (Mg), and potassium (K) was medium to high across the horizons. Zinc (Zn), copper (Cu), iron (Fe), and manganese

(Mn) were also present in medium to high amounts, except for Mn, which showed low values at greater depths.

The soil's electrical conductivity did not show any problems; however, the organic matter content was generally low, typical of tropical soils. The Cation Exchange Capacity (CEC) ranged from low, with 9.59 meq/100 g of soil in the B2 horizon, to high, with 15.49 meq/100 g of soil in the Ap horizon. Bulk density values in the upper horizons ranged between 0.76 to 1.18 t m^{-3}, while deeper horizons showed higher values, ranging from 1.20 to 1.31 t m^{-3}.

Weed control involved two applications of agrochemicals and three manual controls. Fungicide applications, insect pest control, and fertilization were carried out as per the usual practices of local producers.

2.1 Evaluation period

The trial began on June 22, 2023 (day of the year, DOY, 173), with the measurement of physiological variables. Trees of uniform appearance were selected for evaluation, and the trial concluded on November 2, 2023 (DOY 306).

2.2 Measures

2.2.1 Environmental parameters

Meteorological data including precipitation, temperature, relative humidity, atmospheric pressure, and wind speed at 2 m height were recorded every 15 minutes using an automatic station installed at Hacienda "La Clemencia". Data were retrieved through the Weather Link platform.

For the estimation of the daily evapotranspiration of the reference crop, the FAO56 Penman Monteith equation (Allen, 1998) was used, using the DailyET software (Hess, 1999)

2.2.2 Water relations and gas exchange

Leaf water potential at solar noon (Ψ_{leaf}) was measured twice a week on five trees. Additionally, two sunlight-exposed mature leaves per plant were assessed using a pressure chamber.

Stem water potential (Ψ_{stem}) at solar noon was measured twice a week on two mature leaves per plant, near the trunk. These leaves were covered with aluminum foil at least 2 h before pressure chamber measurements.

Stomatic conductance (gs) and net photosynthesis (Pn) were measured twice a week at noon, from DOY 173 to 306. A similar number and type of leaves used for Ψ_{leaf} measurements were evaluated using an IRGA LCPro portable photosynthesis meter.

2.2.3 Trunk micrometer variations

Throughout the trial, trunk micrometric variations were measured in five trees using a dendrometer specifically designed for cocoa trees with easily accessible and low-cost materials, with a prior calibration (Chimarro and Freire, 2023). The device incorporates a KY-024 module with a linear magnetic Hall effect sensor (SS49E), a double differential comparator (LM393), and a potentiometer, providing both analog and digital outputs.

The dendrometer includes a support structure fabricated using additive manufacturing technology in ABS material, featuring a point axis system that transmits trunk expansion or contraction to the module for quantification (see Figures 1A–C). This structure is secured to cocoa trees using a support structure clamp, depicted in Figure 1D.

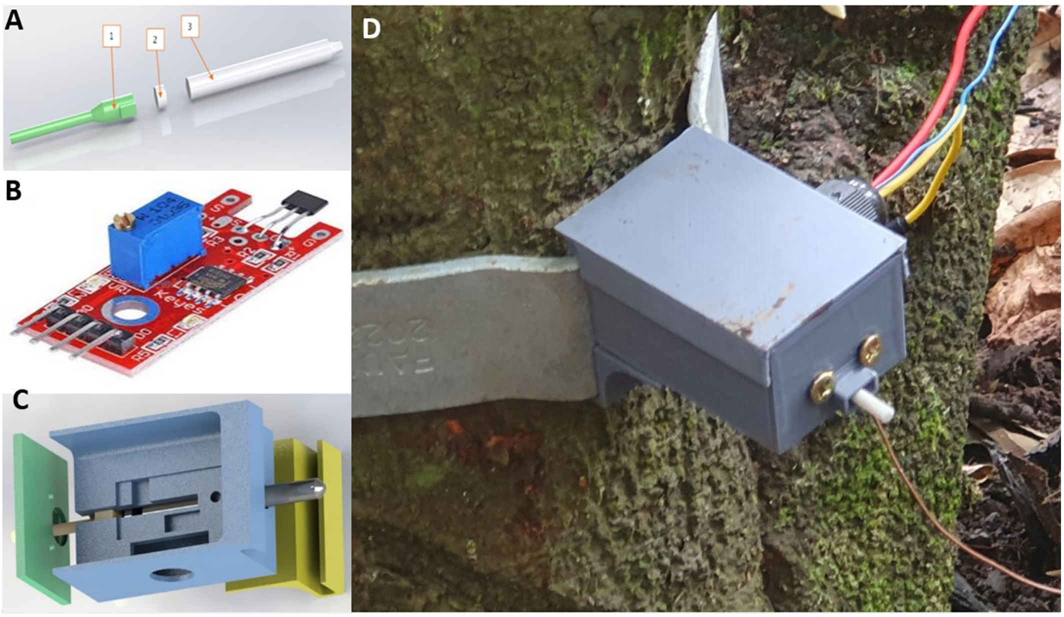

FIGURE 1
Dendrometer structure. **(A)** Hall effect sensor KY-024, **(B)** Point axis system: 1 - photopolymer resin shaft, 2 - neodymium magnet, 3 - steel shaft, **(C)** Dendrometer supporting structure and **(D)** Dendrometer installed on the cocoa tree.

2.2.4 Soil moisture measurement

For soil moisture measurements, an FC-28 sensor was employed, comprising a probe with two resistive electrodes (YL-69) and a YL-38 module with an LM393 comparator. The sensor detects moisture through soil conductivity variation, where a conditioning card monitors voltage levels between the electrodes.

To minimize probe deterioration, the sensor is powered intermittently, performing measurements at one-hour intervals. Soil moisture was monitored at three depths (10, 30, and 50 cm) along the cocoa tree roots and located at 25 cm from the tree trunk.

2.2.5 Data acquisition/transmission

The data acquisition and transmission system used an ESP32 microprocessor, to which the moisture sensors and dendrometers were connected (see Figure 2). This system was responsible for receiving data from these sensors and transmitting it to an IoT server in the cloud via an internet network.

Statistical analysis

A quasi-experimental study was conducted, selecting five trees, which were selected as a random sample within the plots and analyzed as completely random.

3 Results

During the experimental period, Reference Crop Evapotranspiration (ETo) levels reached a cumulative value of 453 mm, progressively increasing and reaching values above 4.5 mm d^{-1} in September, typical behaviour of an area with a tropical climate. (see Figure 3A).

The average maximum temperature was 29°C, and the average relative humidity was 70%. Throughout the trial, the total precipitation was 120 mm. Starting from DOY 226 (August 14), the soil moisture remained below field capacity, a trend that continued until day 290 (October 12), where a series of precipitations occurred that raised the soil moisture above field capacity, allowing for the evaluation of the crop under different moisture conditions, but without reaching water stress (see Figure 3B).

In Figure 4A, the levels of Ψ_{leaf} of the cocoa plant showed variations in its behaviour throughout the evaluated period, with the lowest values observed on days 206 (September 25) and 286 (October 13), measuring -0.67 and -0.51 MPa, respectively. The most positive value occurred on day 192 (July 11), reaching -0.16 MPa, likely influenced by preceding rainfall events as shown in Figure 4B.

Similarly, Ψ_{stem} in cocoa plants showed a comparable trend to Ψ_{leaf}, with the lowest values recorded on days 206 and 286 (October

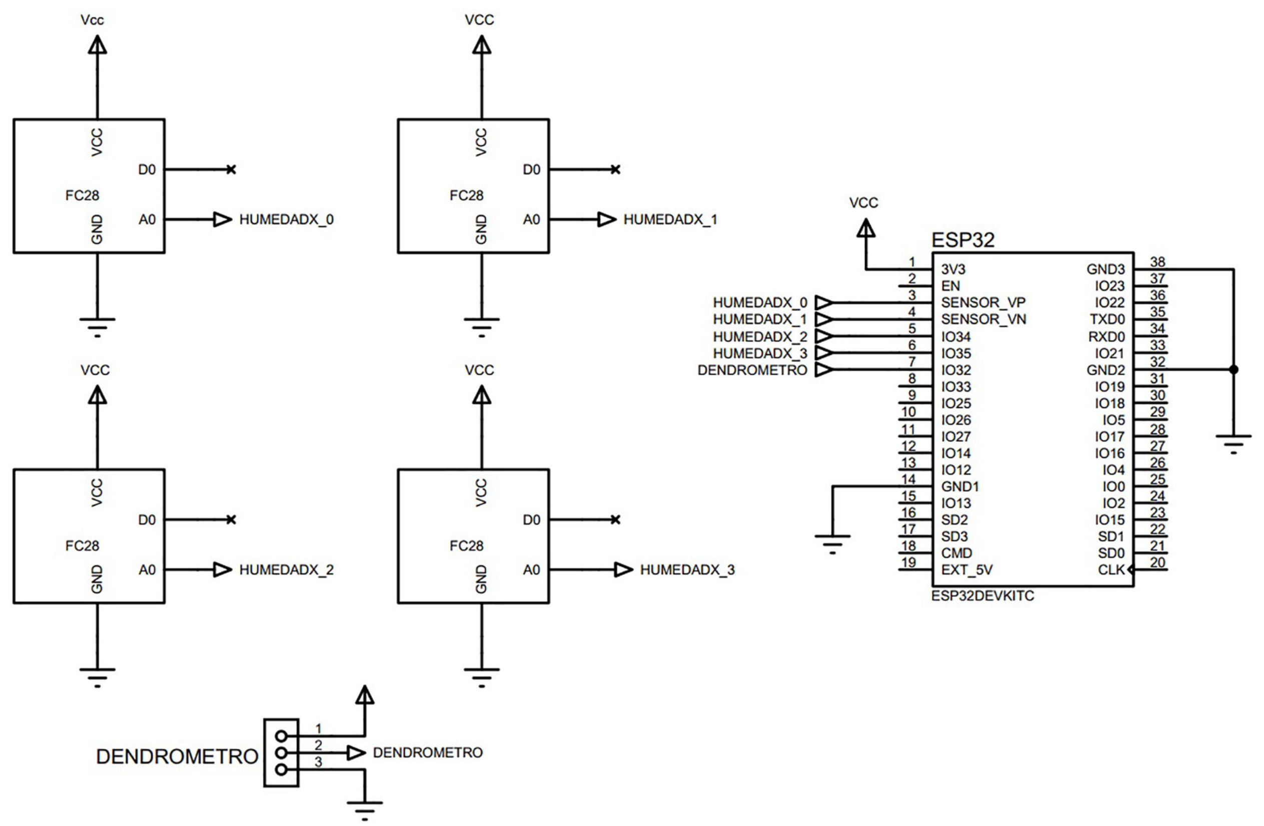

FIGURE 2
Data acquisition and transmission system.

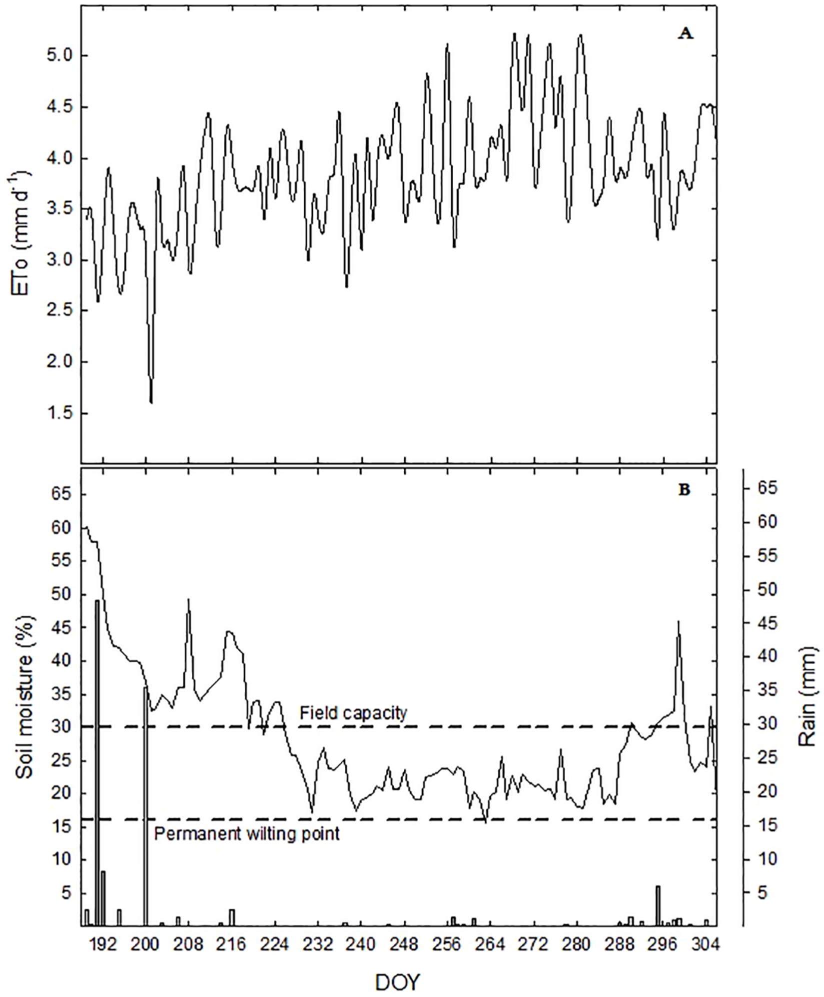

FIGURE 3
Values of the reference crop evapotranspiration (ETo) **(A)**, soil moisture (solid line) and rainfall (vertical bars) **(B)** during the experimental period.

13), measuring -0.30 and -0.32 MPa, respectively. The most positive value of of -0.12 MPa was observed on day 192.

Throughout the trial period, despite decreasing soil moisture values (Figure 3B) and the absence of precipitation events, cocoa trees did not consistently exhibit a decline in water potential.

This resilience could be attributed to osmotic adjustments described by Jiménez-Pérez et al. (2019) in Guasare-type cocoa, where trees maintained turgor even under unfavorable midday conditions when the demand for water evaporation is highest.

Figure 5A illustrates respiration rate (E) levels during the trial, peaking on days 269 (September 26) and 271 (September 28) at 2.57 and 2.62 mmol m^{-2} s^{-1}, respectively. These peaks coincided with minor precipitation events (see Figure 3B).

The lowest E values of 1.12 mmol m^{-2} s^{-1} occurred on days 192 (July 11) and 208 (July 27), with an average of 1.68 mmol m^{-2} s^{-1} throughout the period, which was lower than reported by Agudelo-Castañeda et al. (2018), who described values between 1.91 and 2.15 mmol m^{-2} s^{-1} when evaluating the physiological yield of nine cocoa clones under shade in Rionegro, Colombia.

Stomatal conductance (gs), shown in Figure 5B, reached its highest values on days 248 (September 5) and 278 (October 5) at 150 and 147 mmol m^{-2} s^{-1} respectively. The lowest gs values of 71 mmol CO2 m^{-2} s^{-1} occurred on days 201 (July 20) and 206 (July 25).

The average gs during the evaluation period was 106.55 mmol m^{-2} s^{-1}, comparable to findings by Tezara et al. (2016), who evaluated Forastero and Criollo cocoa trees over 50 years of age on Margarita Island, Venezuela, finding values of 157 and 182 mmol m^{-2} s^{-1} respectively.

CO_2 assimilation (A) peaked on days 299 (October 26) and 248 (September 5), at 8.74 and 8.70 µmol m^{-2} s^{-1} respectively (see Figure 5C), aligning with previous rainfall events. The lowest A values of 4.08 and 4.06 µmol m^{-2} s^{-1} were observed on days 194 (July 13) and 297 (October 24).

The average photosynthetic rate was 6.24 µmol m^{-2} s^{-1}, similar to those obtained by Janani et al. (2019). In this study, using different cocoa genotypes under greenhouse conditions, the response to changes in soil moisture by substantially reducing the photosynthetic rate was

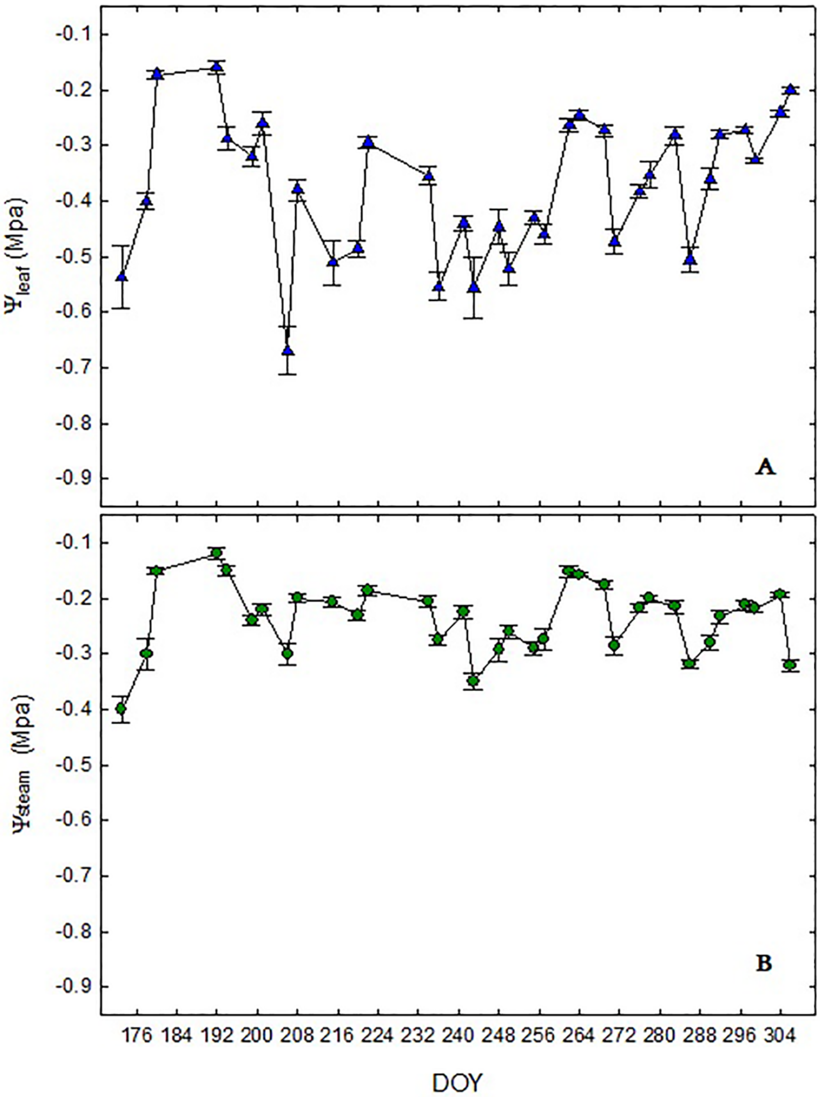

FIGURE 4
Values of midday leaf water potential (Ψ_{leaf}) **(A)** and stem water potential (Ψ_{stem}) **(B)** of adult cocoa trees during the experimental period. The vertical bar indicates the error of the mean. Each point represents the mean of ten values.

demonstrated. Values of 6.48 and 4.09 µmol m^{-2} s^{-1} were reported with two levels of moisture 100 and 50% field capacity respectively.

Figure 6 displays MCDT values, which peaked early in the evaluation period and declined from day 290 (October 18) onward in response to minor rainfall events (see Figure 3A). This rapid response of MCDT to moisture variations aligns with previous studies, highlighting its utility as a cost-effective indicator of plant water status (Ortuño et al., 2006a; García-Orellana et al., 2007; Ortuño et al., 2009; Galindo et al., 2013; Sadka et al., 2023; Wheeler et al., 2023).

In Figure 7, Ψ_{leaf} and Ψ_{stem} demonstrated correlations with ETo, maximum temperature, and vapor pressure deficit (VPD) during the evaluation period. Both Ψ_{leaf} and Ψ_{stem} decreased as these parameters increased. For cocoa trees, Ψ_{leaf} exhibited a stronger correlation with vapor pressure deficit (DPV), while Ψ_{stem} correlated more closely with ETo.

According to Medina and Laliberte (2017), severe stress in cocoa trees is indicated by Ψ_{leaf} values reaching -1.76 MPa, which were not observed during this period (Figure 3A). This suggests that soil type and atypical precipitation patterns may have mitigated water stress conditions.

Osorio Zambrano et al. (2021) reported Ψ_{leaf} values of -0.18 MPa under non-water limiting conditions and -2.48 MPa under stress, indicating that trees in this study did not experience significant water stress (Figure 3B), possibly influencing the observed weak correlations.

In Figure 8, Ψ_{leaf} exhibited the strongest correlation with MCDT, followed by the Ψ_{stem}. In contrast, photosynthetic rate (A) and stomatal conductance did not demonstrate strong correlations during the evaluation period. As gs and CO_2 flux increased, the rate of water loss through transpiration rose, potentially exceeding the rate at which water could be extracted from the soil.

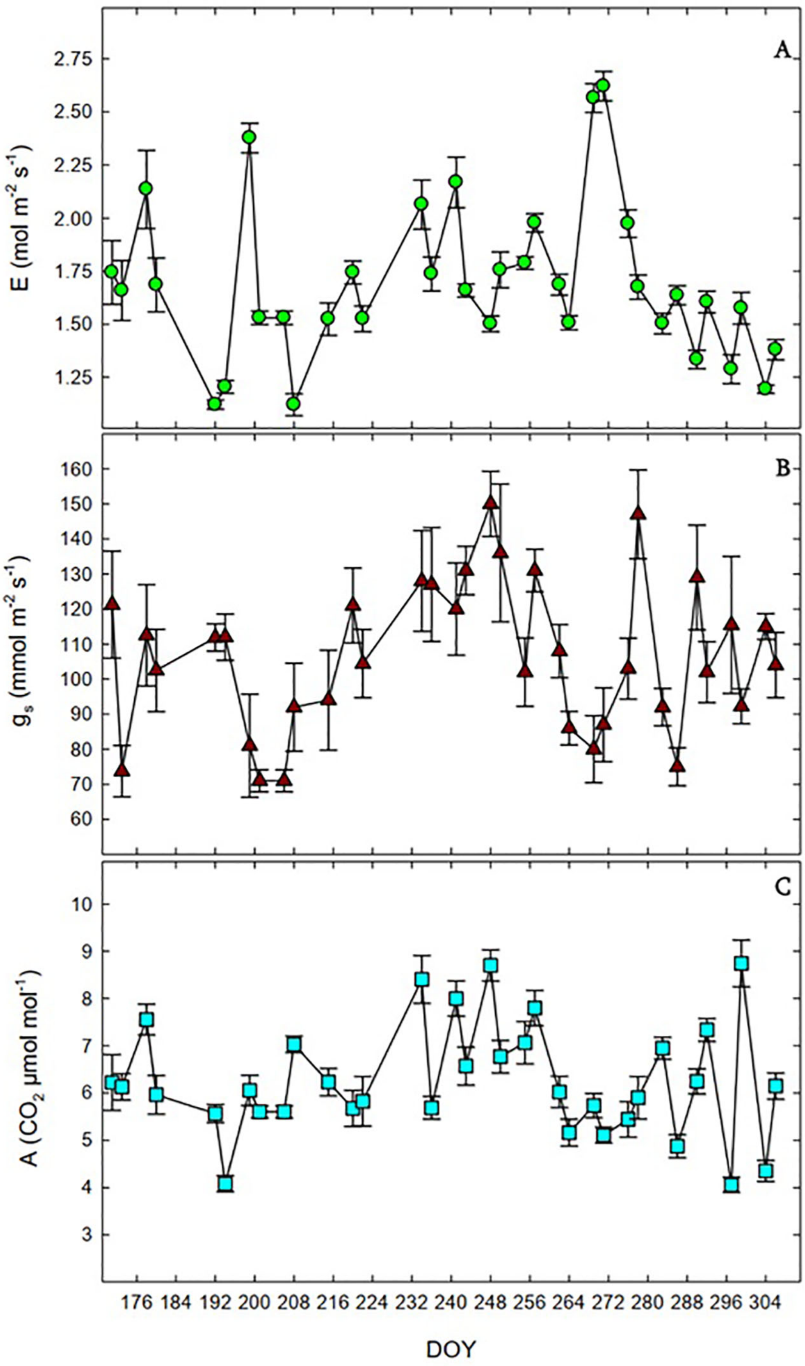

FIGURE 5
Values of transpiration rate (E). **(A)**, stomatal conductance (gs) **(B)** and photosynthetic rate **(A, C)** of adult cocoa trees during the experimental period. The vertical bar indicates the error of the mean. Each point represents the mean of ten values.

However, when soil moisture was sufficient and no limitations were encountered, stomata remained open, allowing for high stomatal activity without an increase in stem diameter. This dynamic was influenced by soil moisture availability and root water uptake capacity.

On the other hand, the relationship with stem contraction was more direct; as water potential became more positive, indicating lower water extraction rates, conducting vessels were less likely to collapse. This facilitated easier water supply to leaves, influencing the curve's variability based on soil water conditions and root water uptake capacity. It is important to consider that water potential integrates plant vascular system water demand and supply rates (McDowell et al., 2022).

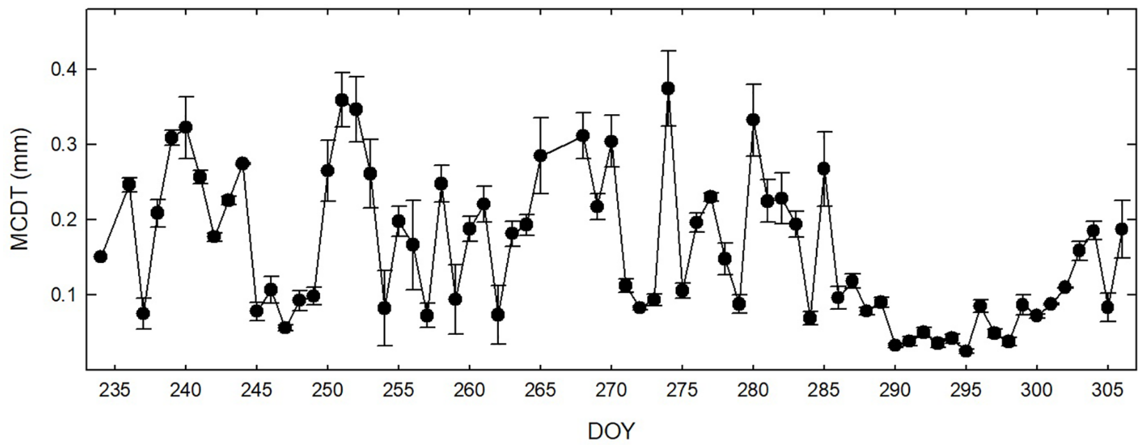

FIGURE 6
Values of maximum daily stem fluctuations (MCDT) of adult cocoa trees during the experimental period. The vertical bar indicates the error of the mean. Each point represents the mean of ten values.

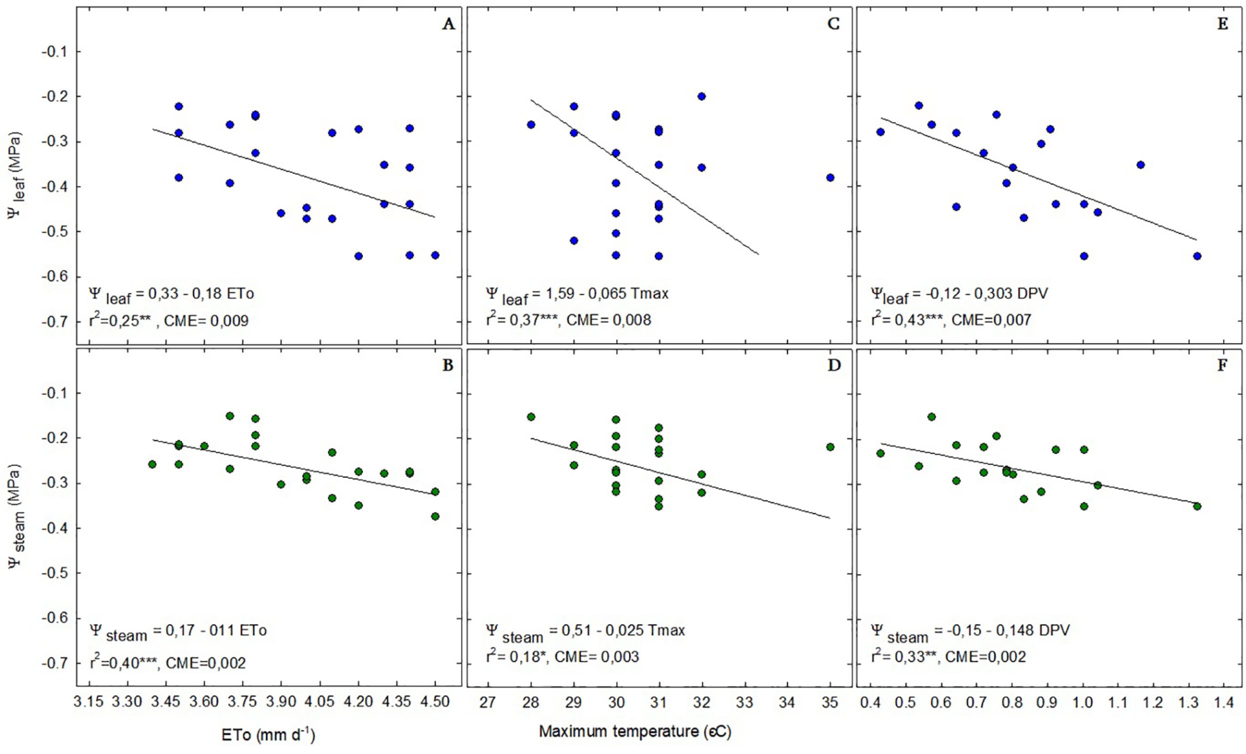

FIGURE 7
Relationship between reference crop evapotranspiration (ETo) **(A, B)**, maximum temperature **(C, D)**, and vapor pressure deficit (DPV) **(E, F)** with leaf water potential (Ψ_{leaf}) and stem water potential (Ψ_{stem}) in adult cocoa trees during the experimental period. Each point represents the mean of ten values. *Statistically significant at P < 0.05. **Very significant P < 0.01, ***Highly significant P < 0.1.

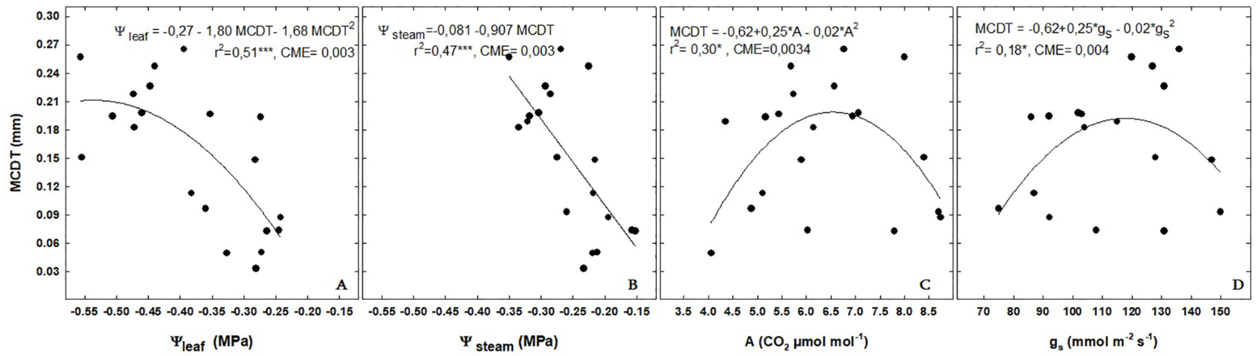

FIGURE 8
Relationship between daily rates of maximum daily stem shrinkage (MCDT) with leaf (Ψ_{leaf}) **(A)** and stem (Ψ_{stem}) water potential **(B)**, photosynthetic rate **(A, C)**, and stomatal conductance (gs) **(D)** in adult cocoa trees during the experimental period. Each point represents the mean of ten values.*Statistically significant at P < 0.05. **Very significant P < 0.01, ***Highly significant P < 0.001.

4 Conclusions

In conclusion, there is a significant relationship between stem potential and MCDT in adult cocoa plants, highlighting MCDT as a robust indicator of the plant water status. This relationship underscores the utility of MCDT in assessing water status in cocoa cultivation. Furthermore, MCDT exhibits stronger correlations with climatic parameters such as DPV and ETo than with maximum temperature, suggesting its potential use for accurately estimating ETo in adult cocoa trees and become a reliable indicator to be used for scheduling, with the intention of automating irrigation, avoiding water deficits that affect the productivity of the cocoa crop. The results obtained are promising, especially because the test was conducted in the field and in a tropical zone, with the use of dendrometers developed, designed and built by members of the work team, making the technology more affordable, increasing the feasibility of its application.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

FF: Conceptualization, Investigation, Project administration, Software, Writing – original draft. YG-O: Conceptualization, Data curation, Formal Analysis, Methodology, Visualization, Writing – original draft. MC: Conceptualization, Investigation, Methodology, Project administration, Supervision, Writing – review & editing, Validation. LV: Data curation, Funding acquisition, Resources, Writing – review & editing. BL: Data curation, Funding acquisition, Resources, Supervision, Writing – review & editing. AC: Data curation, Resources, Software, Writing – review & editing. BR: Data curation, Project administration, Writing – review & editing. WD: Data curation, Project administration, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fagro.2025.1465311/full#supplementary-material

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