JEAP

ISSN: 2525-815X

Journal of Environmental Analysis and Progress

Journal homepage: www.jeap.ufrpe.br/

10.24221/jeap.8.2.2023.4917.086-098

Installation and calibration of sensors for analysis of soil humidity and temperature in eastern Amazon areas

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A R T I C L E I N F O

Received 30 Mar 2022
Accepted 13 May 2023
Published 26 Mai 2023

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A B S T R A C T

Soil moisture and temperature are important components to improve watershed management and natural resource planning. In that way, this article aimed to evaluate the installation and calibration of five sensors (*Drill & Drop*) as well as the consistency of the results obtained for moisture and soil temperature in areas of forest, pasture, forest-pasture transition, and pasture-urban transition in the Itacaiúnas River Hydrographic Area (IRB) in the Eastern Amazon. The results are from April to September 2019, showing different trends between forest and pasture areas. The data consistency analysis efficiently identified measurement errors, especially in the soil's surface layer (10 cm). The highest percentage of error data occurred in the Onça Puma and IFPA rural stations, with 22.8% and 17.6%. On the other hand, these results may be associated with the environmental characteristics of the region, as well as the soil's physical characteristics during each season. The soil temperature and humidity parameters were consistent with data from other meteorological variables (precipitation and mean air temperature) measured by sensors installed in the local hydrometeorological stations. Generally, the temperature and soil moisture measurements were obtained properly and are presented as quality data sources. Thus, it is expected that the results will contribute to enriching the availability of soil data in the IRB and encourage the use of direct measurements given the quantity (and quality) of data obtained using this instrumentation.

Keywords: Direct measurement, drill & drop, water balance.

Introduction

The search for sustainable water resource management practices is essential for human development, considering the increase in global population and limitations in the availability of water resources, especially in some vulnerable regions, where the lack of water is one of the main areas of concern (Pereira et al., 2020). Water has great value for human health, mining, industry, and agriculture, and the giving of this resource in sufficient quantity and quality is strongly influenced by the relationships between water resources and different environmental matrices. In this context, the calculation of the water balance has been one of the most used methods for understanding the dynamics of the soil-water-plant-atmosphere system (de Lima et al., 2005; Moroke et al., 2011).

Studies of water balance components provide critical information that can help to assess the impact of human development and management policies on the environment and territory, indicating viable options for the future (Peña-Arancibia et al., 2021). In addition, knowledge about specific variables (e.g., soil moisture and temperature) is important to better analyze water demands in a region.

Soil temperature is one of the most important hydrological elements in the physical processes, biological ecosystems, and chemical changes (Sanikhani et al., 2018). In addition, soil temperature has applications in agriculture and several areas of water engineering; even though soil temperature data at different profundity are not obtainable for several regions (Feng et al., 2019).

Soil moisture is considered a ‘key’ climate variable, affecting the water and energy swaps on the Earth's surface (Gomes et al., 2017). Soil water content affects energy partitioning and therefore influences evapotranspiration, which is a water balance important element. Hence, the soil’s moisture variability monitoring is relevant because it causes sundry socio-environmental benefits, such as the analysis of natural risk mitigation, agricultural productivity forecasts, crop insurance, ecological health, groundwater recharge, and water quantity (Srivastava, 2017; Long et al., 2019; Singh et al., 2021).

Thus, understanding and quantifying these soil variables are important for the formulation of means of managing hydrological resources and conflict resolution, especially in areas where access to water decreases during the dry season. This creates a contradictory idea, of a hydrological paradox, where the Amazonian environment, which is one of the largest springs on the planet, goes through droughts even with high rainfall and bodies of water, such as those of the Itacaiúnas River Basin (IRB), show intermittent behavior within their regimes and reduced storage capacity (Alves & Beserra Neta, 2018; Silva-Júnior et al., 2021).

The IRB is in the arc of Amazon deforestation, where between 1970 and 2010 about half of the area was already deforested (Pontes et al., 2019). The development of agriculture associated with land use changes and the basin’s occupation has been increasing pasture areas that once were forests (Souza-Filho et al., 2016; Silva Júnior et al., 2017a). The increase in the agricultural area has caused major impacts on water behavior, increasing water and soil degradation in recent decades.

Thus, it is understood that direct observation and field measurements allow more realistic estimates of several environmental variables in a watershed, and the Amazon region suffers from the scarcity of primary data with direct measurement, through adequate equipment. Therefore, this study aimed to analyze the results regarding the installation and calibration of rigs (*Drill & Drop*) to measure humidity and temperature in the forest, pasture, and transition areas in the IRB in the Eastern Amazon. The results are expected to contribute to enriching the availability of soil data in the IRB and encourage the use of direct measurements, given the quantity (and quality) of data obtained using this instrumentation.

Materials and Methods

Study area

The IRB is located between the geographic coordinates 05°10 ' and 07°15' S latitude and 48°37 ' and 51°25' W longitude in the Eastern Amazon, where the Tocantins-Araguaia hydrographic basin is present (Brasil, 2003). Its drainage area is, approximately, 42,000 km^2 and has an accentuated relief that varies between 80 m and 900 m in altitude, with emphasis on the Serra de Carajás (400 m to 900 m). The area contains two types of land cover: rainforest and mountain savanna. However, there are pastures that surround a mosaic extensively and come from remaining forests (Figure 1). In the region, indigenous lands and conservation units are protected by law, occupying 11,700 km^2, corresponding to approximately one-quarter of the basin area (Souza-Filho et al., 2016).

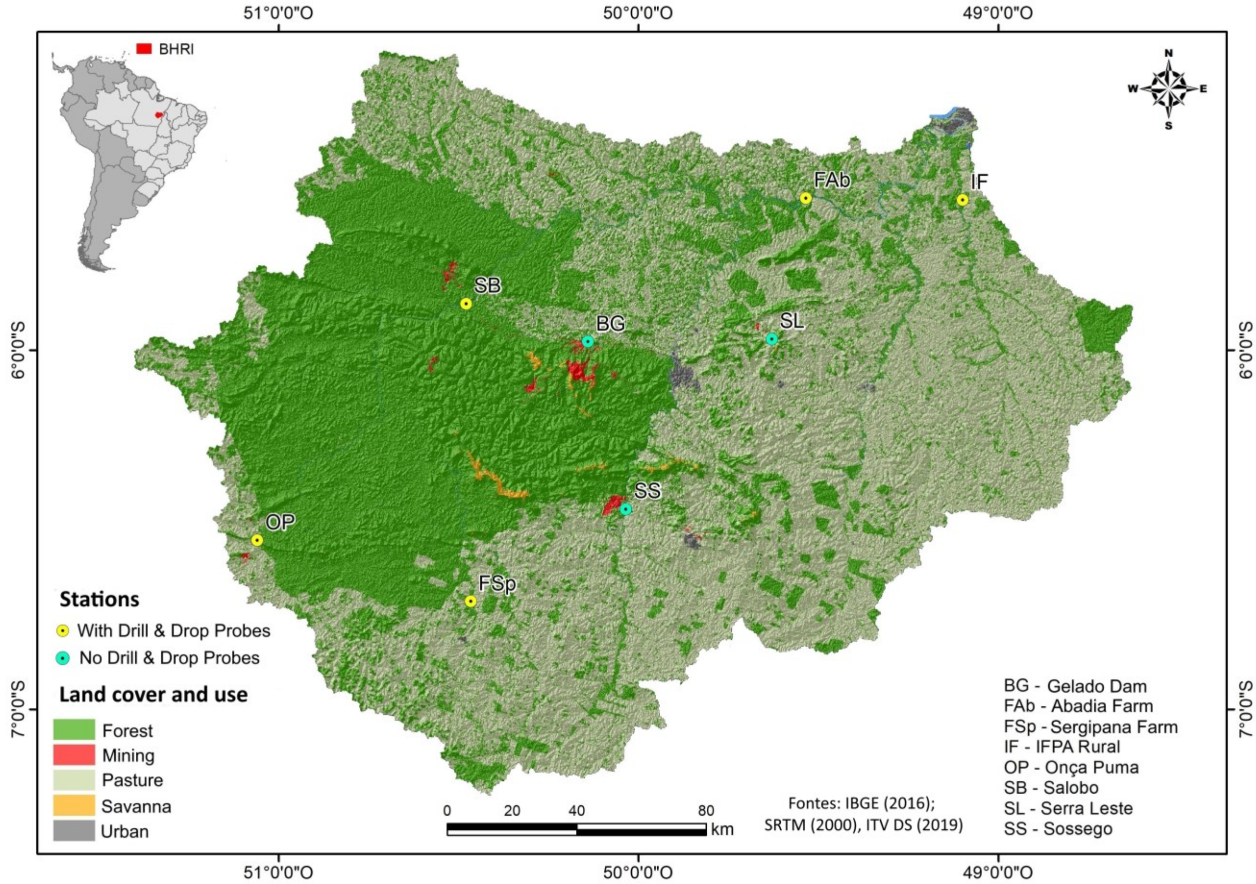

Figure 1. Map of the Itacaiúnas River Basin (IRB), in the state of Pará, showing the presence of hydrometeorological stations and the different kinds of land uses and land cover. Font: Silva Júnior et al. (2022).

The region's climate, in eastern Amazon, is typical of a monsoon (Am), which corresponds to tropical rain (hot and humid), with an average air temperature above 26°C (INMET, 1992; Alvares et al., 2014). Specifically, in the IRB region, the average recorded air temperature is 27.2°C, with the lowest annual temperature being 26.6°C, which occurs in January; the highest temperature is 28.1°C, which occurs in September. The rainy season, which stands between November and May, and the dry season which vary between June and October are well defined, whose total annual precipitation indices can vary between 1,800 mm and 2,300 mm under the rainy season and between 10 mm and 350 mm under dry season (de Moraes et al., 2005; Silva Júnior et al., 2017a).

Soil moisture and temperature measuring sensor

Soil moisture is among the most chief and recognized variables in watershed monitoring (Vereecken et al., 2008; de Souza et al., 2011; Li et al., 2019). Many techniques and devices allow the quantification of water in the soil: thermogravimetry, neutron scattering, and soil resistivity, among others, like time domain reflectometry (TDR), frequency domain reflectometry (FDR), and capacitance which are dielectric techniques (Su et al., 2014). Among these, the FDR stands out as one of the most used today due to its lower vulnerability to different environmental conditions (Teruel, 2017).

The techniques based on capacitance and FDR have an oscillating circuit and part of the sensor that is mortised in the ground. The FDR sensors consist of a set of circular metal rings that form a capacitor with the ground as the dielectric. A tuned circuit from the capacitor works with the oscillator, and from the changes in the operating frequency one can detect changes in the soil moisture content (generally ranging from 10 to 150 MHz). Thus, it is possible to calculate the dielectric permittivity of a medium by measuring the time that the charge of a capacitor that uses it as an insulator (Whalley et al., 1992; Gardner et al., 1997; Minet et al., 2010).

The soil measurement probe used in this study is called *Drill & Drop* (Sentek Technologies, 2016), which also has a sensor based on FDR capacitive technology. Its design is thinner (2.5 cm - 3.0 cm in diameter) than that of most used; it is also fully encapsulated (electronic protection) and conical. Due to its direct installation, the soil does not suffer disturbance from its surroundings, allowing measurements under their real conditions. It is available in four lengths (30, 60, 90, and 120 cm); in this case, a length of 90 cm was used, with sensors every 10 cm along the length of the probe (Figure 2).

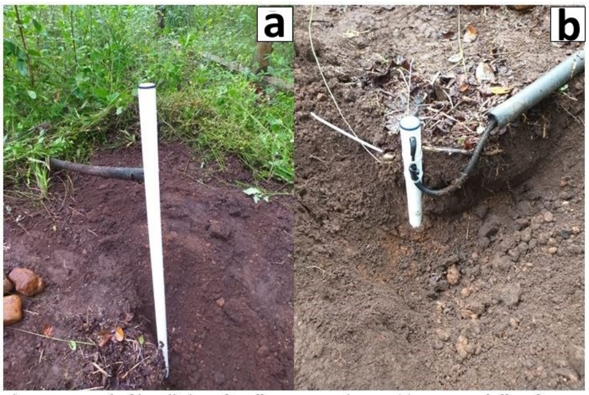

Figure 2. Record of installation of *Drill & Drop* probes. In (a), a 90 cm *drill & drop* sensor was fixed near each station. In (b), the connection cable is connected to the *datalogger* device. Font: Silva Júnior et al. (2022).

Considering this research, in April 2019, five 90-cm long probes were installed and distributed near the IRB hydrometeorological stations (Figure 1), namely: Onça Puma (OP), Salobo (SB), IFPA Rural (IFPA), Abadia Farm (FAb) and Sergipana Farm (FSp). After being configured and connected to a *data logger*, these devices allow the direct measurement of three soil parameters: moisture, temperature, and salinity, providing average, maximum, and minimum values every 10 cm at nine different depths; therefore, 81 soil data points for each probe, were recorded every 1 hour.

The raw data measured by the probe are converted using a calibration equation of the soil volumetric water content. This equation is expressed as the water's volume per unit of soil's volume, i.e., 1 mm = 1 mm of height per square meter of soil area = 1 liter. If a sensor reads 1 mm, there is 1 mm of water content in a 10-cm-thick slice of soil in volume. For this layer (and only this layer), this is equivalent to volumetric water content in the soil of 1% (Sentek Technologies, 2016).

The probes were installed at strategic points (Table 1) because the knowledge of the soil's variables behavior in different areas of vegetation cover and land use matters for soil–atmosphere interactions observation in these areas since soil temperature and moisture are essential components for estimating the water balance in the IRB.

Table 1. Main information of the stations with probes installed in the Itacaiúnas River Basin (IRB), in eastern Amazon areas. Font: Silva Júnior et al. (2022).

Station	ID NOAA	Name of the watercourse	Municipality	Location		Altitude (m)
				Latitude	Longitude	
Onça Puma (OP)	822083D6	Cateté River	Ourilândia do Norte	06°31'46" S	51°03'33" W	259
Salobo (SB)	822090A0	Itacaiúnas River	Marabá	05°52'17" S	50°28'44" W	178
Abadia Farm (FAb)	8220B64C	Itacaiúnas River	Marabá	05°34'39" S	49°32'05" W	134
IFPA Rural (FI)	8220E630	Sororó River	Marabá	05°34'57" S	49°05'57" W	111
Sergipana Farm (FSp)	8220D3AA	Água Azul River	Água Azul do Norte	06°41'58" S	50°27'57" W	259

Parameter reading

Data from the soil measurement sensors were recorded from the beginning of April 2019 to the beginning of September 2019; therefore, there were five months of data. Climatologically, this period corresponds to the transition period in the region, between the rainy season end and the dry season beginning. The records consist of hourly measurements of soil temperature, humidity, and salinity at nine depth levels every 10 cm.

Data analysis and consistency

There are three important reasons for directly applying quality control procedures to the obtained data: (i) ensuring that the information is properly generated; (ii) identifying erroneous data involving inadequate decision-making; and (iii) detecting and solving problems for correct maintenance in the stations and periodic sensor calibration (Doraiswamy et al., 2000).

The quality control methods applied in this study are listed as follows: 1) range/limit test (fixed or dynamic), 2) step test, and 3) internal consistency test. Data that do not pass the fixed-range test should be classified as incorrect. Data rejected by other tests should be flagged as suspicious and validated by manual inspection.

The range test lies on enforcement specifications for each sensor and physical/climatic extremes for each location and variable. According to the manual, the limits of different variables may depend on local climatic conditions and a given season.

Any observation above the maximum or minimum value allowed is duly flagged. Measured data must be within this upper and lower limit to be considered useful (Meek & Hatfield, 1994; Shafer et al., 2000; Feng et al., 2004). There are two types of intervals: fixed (physical and instrumental) and dynamic. The fixed range test compares the value of a variable with established extreme values. Any observation that does not fall within the acceptable range is flagged as incorrect and is not validated by subsequent testing.

Quality control tests based on time consistency (step test) lie in the comparison of the variation between successive measurements. If the difference exceeds a permitted value, a different value for each parameter, both observations will be flagged as suspicious (Shafer et al., 2000). Therefore, this test verifies the excessive rate of change in two consecutive values (Estévez et al., 2011).

In turn, the internal consistency test is based on checking the physical or climatological consistency of each observed parameter or on the relationship between two measured variables (Grüter et al., 2001). For example, meteorological variables measured at the same location and time must be consistent, otherwise, the measurements will be suspect. Although, an average value always will be fewer than the maximum instantaneous value, or the precipitation that occurs in 6 h will always be considered less than or even equal to the precipitation of 24 h (Vejen et al., 2002).

The procedures based on the tests applied for soil temperature and humidity, with the limits suggested for these variables and ranges proposed by some authors (REF), are shown in Table 2. As maintained by the World Meteorological Organization (WMO, 2017), the range limits determination for soil moisture is in the proof-of-concept phase yet. Thus, these values are not included in the step test procedure for this variable.

Table 2. Quality control procedures applied to hourly data of soil temperature and moisture. Font: Sentek Technologies (2016); WMO (2017); Reek et al. (1992); Feng et al. (2004).

Validation procedure	Soil moisture (%)	Soil temperature (°C)		
Range test	$0 \leq Us \leq 100\%$	$-20 \leq Ts \leq 60°C$		
Step test	---		Limit/suspicious	Limit/error
		$Ts_{(10\ to\ 40\ cm)}$	0,5°C	1°C
		$Ts_{(50\ to\ 90\ cm)}$	0,3°C	0,5°C
Internal consistency test	$Us_{max} > Us_{med} > Us_{min}$ or $Us_{max} > Us_{min}$	$Ts_{max} > Ts_{med} > Ts_{min}$ or $Ts_{max} > Ts_{min}$		

Us = soil moisture (%); Us_{max} = maximum soil moisture; Us_{med} = mean soil moisture; Us_{min} = minimum soil moisture; Ts = soil temperature (°C); Ts_{max} = maximum soil temperature (°C); Ts_{med} = mean soil temperature (°C); Ts_{min} = minimum soil temperature (°C).

Results and Discussion

In evaluating the range test for the soil temperature and moisture records, data outside the range of extreme values were not detected (Table 2) and therefore were validated for subsequent tests. The step test consists of verifying the rate of change in the instantaneous data for possible detection of unreal peaks or jumps in values caused by sensors. The tests were applied, and the literature determined the air and soil temperature limits (WMO, 2017) which are shown in Table 2. Table 3 shows the results, which presents the records identified as suspicious and errors in the percentage proportion of the total number of observations.

Table 3. Parameters (Par.) of the step test of air temperature (Tar) and soil temperature (Ts) at nine soil depth levels (cm) for all seasons in eastern Amazon areas from the beginning of April 2019 to the beginning of September 2019. Font: Silva Júnior et al. (2022).

	Onça Puma		Salobo		Abadia Farm		IFPA Rural		Sergipana	
	Suspicious	Error	Suspicious	Error	Suspicious	Error	Suspicious	Error	Suspicious	Error

Par.	(%)									
Tar (°C)	5,4	0,0	3,8	0,0	2,4	0,0	-	-	6,8	0,1
Ts10	38,0	22,8	8,8	0,3	33,4	12,1	35,7	17,6	29,1	0,3
Ts20	13,9	0,1	0,1	0,0	0,0	0,0	0,6	0,0	0,0	0,0
Ts30	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Ts40	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Ts50	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Ts60	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Ts70	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Ts80	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Ts90	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0

The location of error data is mainly in the surface layer of the soil (10 cm), with no inconsistent data in the subsequent layers. Note that the highest percentage of errors was identified at the Onça Puma station (22.8%), followed by the IFPA Rural station (17.6%) may be associated with the environmental characteristics of the region (forest, pasture, transition), as well as with the physical characteristics of the soil relevant to each season. At Salobo and Sergipana Farm stations, the lowest percentages of errors in the series of records were observed (0.3%). Questionable results are attributed to the low quality of the data due to the nonexistent or mixed quality control methods (Meek & Hatfield, 1994; Estévez et al., 2011).

Still, the behavior observed may be associated with a greater hourly thermal amplitude in the soil throughout the day. Table 4 shows the result of a complementary analysis of the step test, in which the proportion of errors recorded at predominant times throughout the day is shown, but only for the 10 cm layer. Notably, at times between 4:00 pm and 7:00 pm, there is a pattern of a higher percentage of errors, most likely due to the environmental characteristics of the region (sudden fluctuations in temperature, precipitation, humidity, etc.), which is reflected in the soil's physical characteristics at each of the stations.

Table 4. Hourly analysis of the proportion of errors (%), according to the step test for soil temperature in the 10 cm layer. Font: Silva Júnior et al. (2022).

Hours with predominant errors	**Onça Puma**	**Salobo**	**Abadia Farm**	**IFPA Rural**	**Sergipana Farm**
1		-	-	0.33	-
10	0,25	-	-	-	-
13	0,25	-	-	-	-
14	0,76	-	-	-	20,0
15	8,91	-	-	-	20,0
16	18,1	20,0	1,44	3,62	20,0
17	17,8	40,0	24,5	18,1	-
18	17,8	20,0	26,0	22,7	-
19	17,3	20,0	24,5	23,7	-
20	13,0	-	19,2	18,4	20,0
21	4,83	-	4,33	11,5	20,0
22	1,02	-	-	1,64	-
Total observations	**393**	**5**	**208**	**304**	**5**

Considering the application of the internal consistency test, soil moisture and precipitation relationships, soil temperatures, and mean air temperature on continuous days in the recorded period were verified. Figures 4-8 show the behavior for the first six soil levels (10 to 60 cm).

The number of hours of soil moisture monitoring was not equal between seasons (Abadia Farm = 3.674 h, Sergipana Farm = 3.693 h, IFPA Rural = 3.746 h, Onça Puma = 1.962 h, and Salobo = 3.692 h). In Figure 3, only the interval of joint monitoring of precipitation for these stations (12/04/2019 to 09/05/2019) is observed. There is a greater accumulated rainfall volume at the Onça Puma station, followed by the Salobo, Sergipana Farm, Abadia Farm, and IFPA Rural stations. Figure 3 shows the transition period, in which it is observed that for 1,000 h monitored it rained on average approximately 200 mm, while in the following hours until 3,000 h the cumulative values were 50 mm.

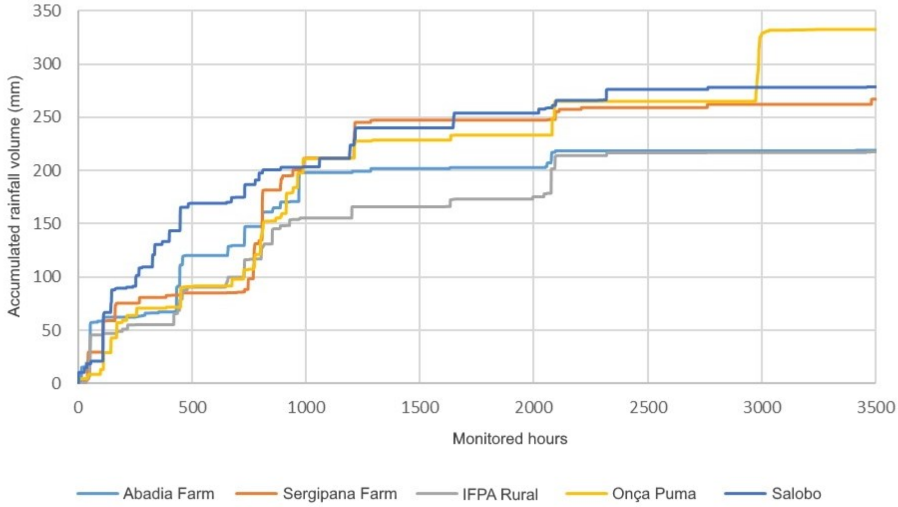

Figure 3. Period of hours monitored for accumulated precipitation in all seasons in eastern Amazon areas from the beginning of April 2019 to the beginning of September 2019. Font: Silva Júnior et al. (2022).

In another form of analysis, the internal consistency of the data was graphically verified by observing rainfall (> 0 mm) and soil moisture in the first three layers (10, 20, and 30 cm). According to this, three-hourly observations were adopted to measure the mean values (Figures 4, 5, 6, 7, and 8). A weak relation was observed between rainfall and soil moisture in the 10 cm layer (Abadia Farm = 0.24; IFPA Rural = 0.20; Onça Puma = 0.28; Salobo = 0.24), except for the Sergipana Farm station. However, as expected, there was a positive pattern between these variables. In general, there is a trend of increasing soil moisture with depth. From the surface layers, water can be drained and percolated into deeper layers. Nevertheless, the basin lost 8.1% of its water retention capacity over three decades, that is, annual soil water storage changes in a watershed are water's balance important elements (Silva-Júnior et al., 2021).

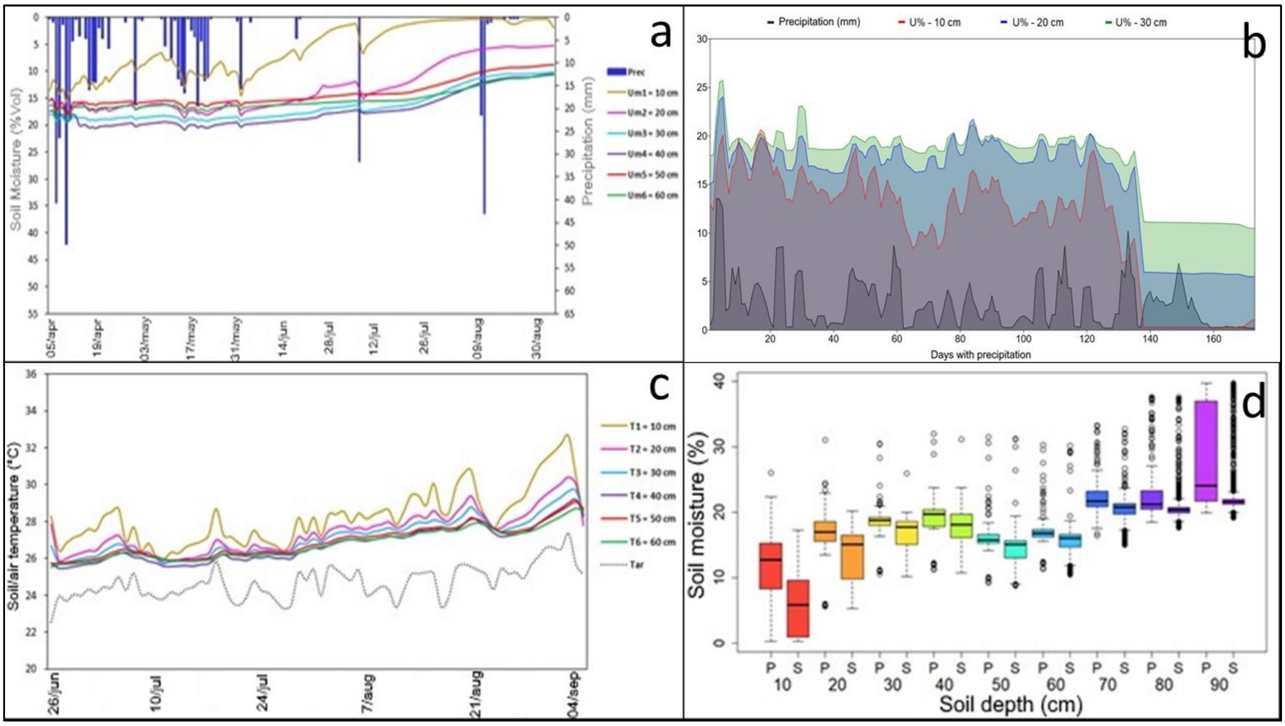

Figure 4. Internal consistency analysis for hourly data of soil temperature and humidity for the Onça Puma station (Forest - Pasture Transition), in eastern Amazon areas. P = precipitation > 0 mm; S = precipitation = 0 mm. Font: Silva Júnior et al. (2022).

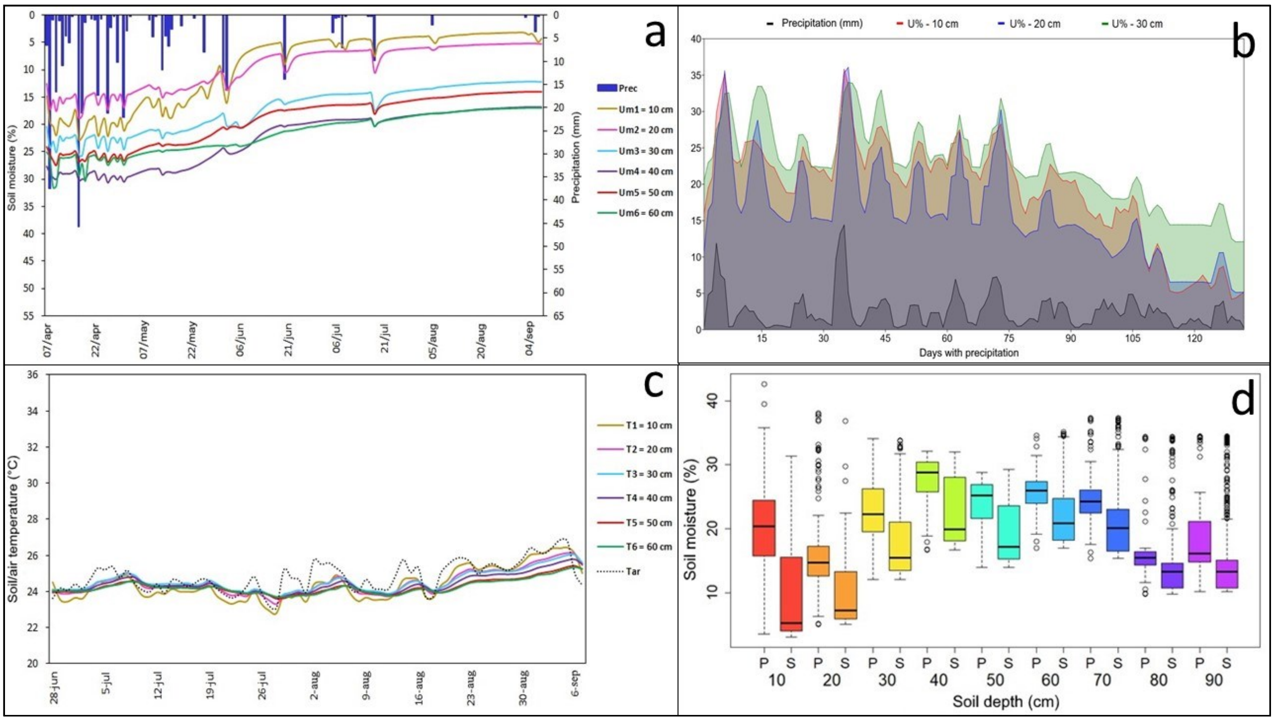

Figure 5. Internal consistency analysis for hourly data of soil temperature and humidity for the Salobo station (Forest), in eastern Amazon areas. P = precipitation > 0 mm; S = precipitation = 0 mm. Font: Silva Júnior et al. (2022).

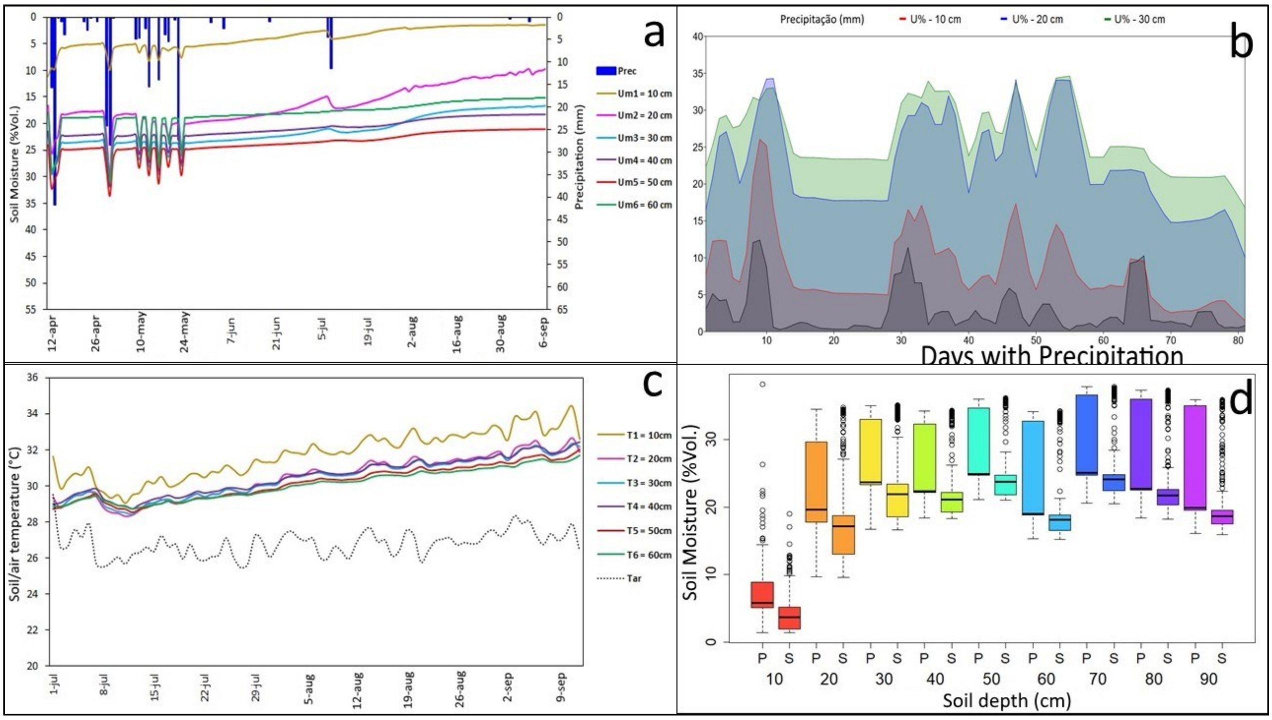

Figure 6. Internal consistency analysis for hourly data of soil temperature and humidity for the Abadia Farm (Pasture) station, in eastern Amazon areas. P = precipitation > 0 mm; S = precipitation = 0 mm. Font: Silva Júnior et al. (2022).

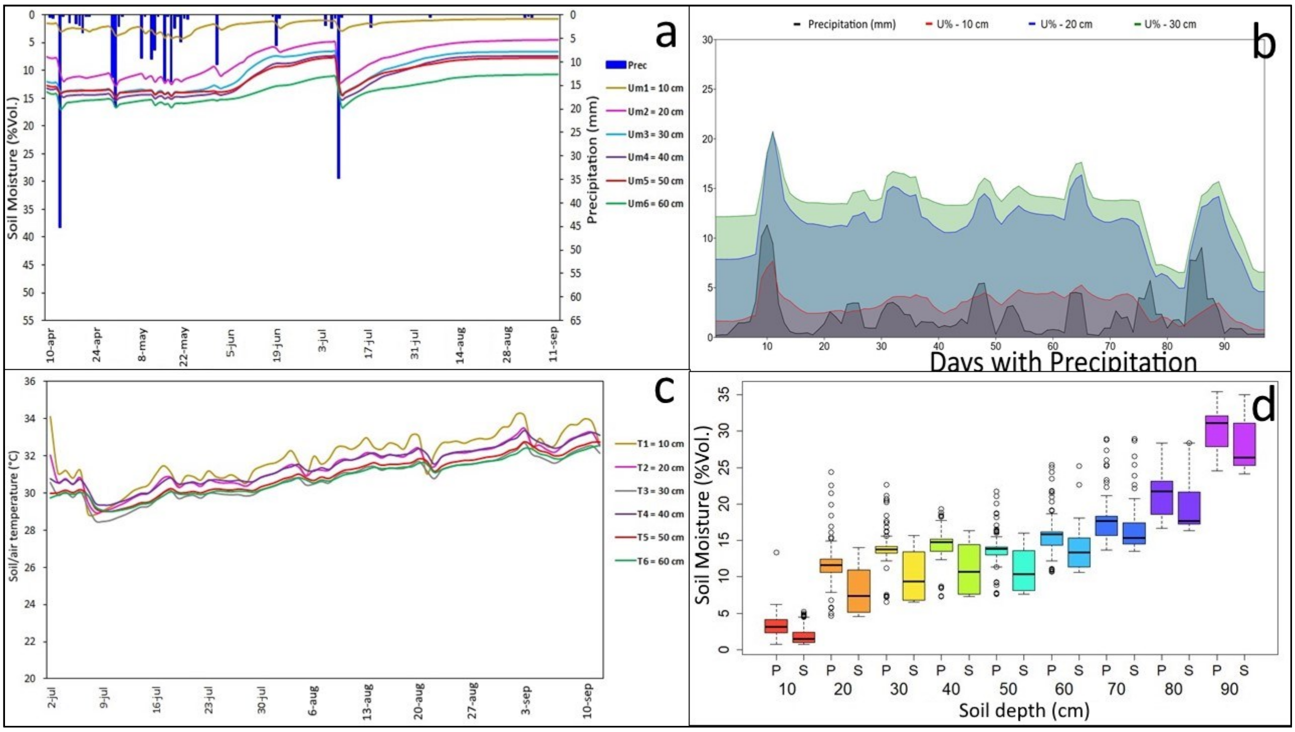

Figure 7. Internal consistency analysis for hourly data of soil temperature and humidity for the IFPA Rural station (Transition Pasture -Urban), in eastern Amazon areas. P = precipitation > 0 mm; S = precipitation = 0 mm. Source: Silva Júnior et al. (2022).

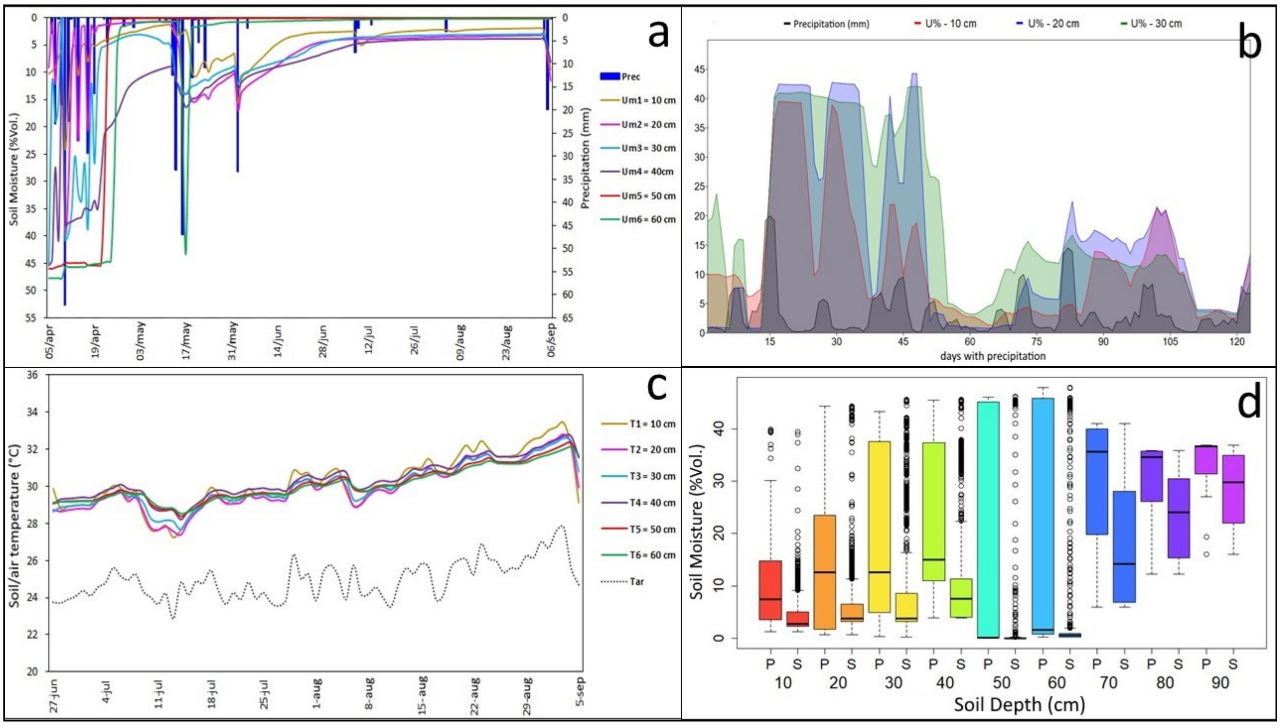

Figure 8. Internal consistency analysis for the hourly data of soil temperature and humidity for the station in Sergipana Farm (Pasture), in eastern Amazon areas. P = precipitation > 0 mm; S = precipitation = 0 mm. Source: Silva Júnior et al. (2022).

In addition, losses due to evapotranspiration occur, which are directly influenced by the type of vegetation, wind regime, air temperature, humidity, and incidence of solar radiation. With the increase in depth, the influence of wind and temperature are attenuated; consequently, the water content and the attributes of the adjacent and underlying layers begin to contribute more effectively to the moisture balance in each soil range. This finding agrees with the positive correlations (moderate to strong) observed between moisture levels in different layers. Stations Abadia Farm (Figure 6d) and Sergipana Farm (Figure 8d) show a wide range of humidity values for the rainfall occurrence observations, unlike the periods without precipitation.

These results are possible due to the soil texture. Sandy soils may have facilitated drainage; thus, after the precipitation event, the soil moisture can quickly increase and be rapidly reduced after precipitation ceases. On the other hand, the Onça Puma (Figure 4a and d) and IFPA Rural (Figure 7a and d) stations had lower amplitudes of moisture data, regardless of the occurrence of precipitation. This result may be indicative of relatively more clayey soils with lower drainage capacity. This analysis corroborates a study conducted by Tong et al. (2020), who showed a positive correlation between soil water and higher clay content and a negative correlation with sand and silt percentage. Finally, the influence of soil texture and meteorological factors was determined on the spatial-temporal variability in soil water content in a study conducted in the Liudaogou watershed, China (Tong et al., 2020).

In addition to the factors associated with soil attributes, the volume, intensity, and frequency of rainfall have a direct influence on soil moisture. This result can be observed in Onça Puma and Sergipana Farm stations (Figures 4 and 8), which stand out with the highest rainfall accumulations of 475.6 and 417.2 mm in the observed period, respectively. However, at the Onça Puma station (Figure 4a), 2 days (14/08/2019 and 15/08/2019) with cumulative rainfall were identified and their dubious behavior can be explained by two factors: the first is by not showing symmetry to the soil moisture values, and the second is because there is no formation of precipitation clouds in the GOES 16 satellite images (channel 13); there is also no occurrence of rain over the region in the daily maps of interpolated precipitation, which were acquired from Monitoring Climate Change over Brazil, part of the Center for Weather Forecasting and Climate Studies - CPTEC/INPE.

Another factor that should be considered is the groundwater level, which may influence the subjacent layers (Stanly et al., 2021). This factor is especially important for the Sergipana Farm station, which is less than 20 m away from the Água Azul River. At the Sergipana Farm, moisture peaks were observed in the initial monitoring periods, which differ from the patterns observed throughout the period (Figure 8). This increase in soil moisture may be due to rainfall occurring in periods prior to the start of monitoring. There is a correspondence between the soil temperature measurements and the air temperature measurements in all stations, except for the IFPA Rural station, which had problems with air temperature records (Figures 4c, 5c, 6c, 7c, and 8c).

Conclusion

In evaluating the range test for soil temperature and moisture, records outside of the intervals established in the literature were not observed and were validated for the following tests. In the results of the step test for soil and air temperature, errors were identified mainly in the surface layer of the soil (10 cm). The stations Onça Puma and IFPA Rural had the highest percentage of data error at 22.8% and 17.6%, respectively. On the other hand, these results may be associated with the environmental characteristics of the region (forest, pasture, and transition), as well as the physical characteristics of the soil relevant to each station.

The results of the installation, calibration, and monitoring of soil temperature and moisture parameters were consistent with data from other meteorological variables (precipitation and mean air temperature) measured by other sensors. In this sense, it is valid to say that direct measurements of soil moisture and temperature are sources of quality data to efficiently monitor these soil variables.

Acknowledgments

The authors thank the Instituto Tecnológico Vale-ITV for Sustainable Development for technical and logistical support.

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