**Abstract**

Soil moisture plays a key role in hydrological, biogeochemical, and energy budgets of terrestrial ecosystems. Accurate soil moisture measurements in remote ecosystems such as the Amazon are difficult and limited because of logistical constraints. Time domain reflectometry (TDR) sensors are widely used to monitor soil moisture and require calibration to convert the TDR’s dielectric permittivity measurement ($K_a$) to volumetric water content ($\theta_v$). In this study, our objectives were to develop a field-based calibration of TDR sensors in an old-growth upland forest in the central Amazon, to evaluate the performance of the calibration, and then to apply the calibration to determine the dynamics of soil moisture content within a 14.2-m-deep vertical soil profile. Depth-specific TDR calibration using local soils in a controlled laboratory setting yielded a novel $K_a$–$\theta_v$ third-degree polynomial calibration. The sensors were later installed to their specific calibration depth in a 14.2-m pit. The widely used $K_a$–$\theta_v$ relationship (Topp model) underestimated the site-specific $\theta_v$ by 22–42%, indicating significant error in the model when applied to these well-structured, clay-rich tropical forest soils. The calibrated wet- and dry-season $\theta_v$ data showed a variety of depth and temporal variations highlighting the importance of soil textural differentiation, root uptake depths, as well as event to seasonal precipitation effects. Data such as these are greatly needed for improving our understanding.
1 | INTRODUCTION

Soil moisture refers to water content present in the soil pore space. It strongly affects land–atmosphere feedbacks because of its central role in hydrological, energy and biogeochemical cycling. For example, evapotranspiration as mediated by vegetation is largely controlled by soil moisture availability, which subsequently regulates local and regional cloud formation and rainfall (Eltahir, 1998). The energy used to evaporate water from soil and plant surfaces affects the partitioning of incoming radiation, and therefore soil moisture has a direct effect on the surface radiation balance (Lei, Crow, Holmes, Hain, & Anderson, 2015). Thus, knowledge of soil moisture availability and its dependency on environmental and edaphic conditions can be used for predictions of temperature and rainfall patterns (Robock, 2015). Soil moisture is an important control on infiltration and percolation into a soil profile (i.e., the vadose zone), overland flow, interflow generation, and groundwater recharge (Koster et al., 2004; Sheffield & Wood, 2008). It also has strong biogeochemical effects through impacts on microbial activity, soil respiration and nutrient cycling (Austin et al., 2004), as well as forest ecosystem health and services (e.g., C storage and agricultural production).

Changes in soil moisture are driven by many factors, which presents a challenge for predicting soil moisture over space and time (Yoo & Kim, 2004). However, quantifying soil moisture is critical for understanding how changes in land surface and climate affect the functioning of the global system (Robock et al., 2000; Sheffield & Wood, 2008). Accurate measurements of soil moisture are important for validating and improving land surface, for remote sensing of soil moisture (Dorigo et al., 2011) across multiple scales (Brocca, Morbidelli, Melone, & Moramarco, 2007; Famiglietti et al., 1999; Koster et al., 2009), and for identifying trends associated with climate change and disturbance (Robock, Mu, Vinnikov, Trofimova, & Adamenko, 2005). Soil moisture is considered an essential climate variable in the Global Climate Observing System (GCOS; WMO-GCOS, 2016).

The Amazon is the largest continuous tropical forest in the world, representing 53% of the global tropical area (Negrón-Juárez et al., 2018). Because of the strong recycling effects, evapotranspiration is responsible for up to 50% of the annual rainfall in the Amazon (Salati, Dallolio, Matsui, & Gat, 1979; van der Ent, Savenije, Schaefli, & Steele-Dunne, 2010). Root uptake of soil water and subsequent plant transpiration provide the largest contribution to water recycling in the Amazon (Kunert et al., 2017). Understanding of soil moisture dynamics in the Amazon is complicated due to the regional climatic differences (Negrón-Juárez, Li, Fu, Fernandes, & Cardoso, 2009; Sombroek, 2001), soil characteristics (Quesada et al., 2010), and floristic composition (ter Steege et al., 2013) that alter the exchange of water in the atmosphere–biosphere continuum (Gimenez et al., 2019). Although challenging, continuous measurements of soil moisture in the Amazon have demonstrated the importance of deep water uptake to transpiration during the dry season (Bruno, da Rocha, de Freitas, Goulden, & Miller, 2006; Negrón-Juárez et al., 2007; Nepstad et al., 1994).

Accurate measurements of volumetric water content ($\theta_v$) are important for a variety of reasons. For example, a major interest of the Next Generation Ecosystem Experiments-Tropics (NGEE-Tropics) project (https://ngee-tropics.lbl.gov/) is to understand the effect of droughts and dry seasons on forests in the central Amazon and the vulnerability of these forests to water stress and mortality (Fontes et al., 2018; Gimenez et al., 2019; Solander et al., 2020). Because $\theta_v$ varies significantly with depth and time, high-time-resolution measurements that span the root zone and below are needed. Transpiration demand, for example, is typically higher in the shallow soils than in deeper soils (Broedel, Tomasella, Candido, & von Randow, 2017; Negrón-Juárez et al., 2007), requiring characterization of depth variations in $\theta_v$ that extend beyond the typical 1- to 2-m measurement zone. Time series of $\theta_v$ are especially important in monsoonal climates because water used to meet transpiration demand during the dry season...
can be supplied from the previous rainy season (Negrón-Juárez et al., 2007), since water can remain plant available in the soil for weeks to months (Dirmeyer, Schlosser, & Brubaker, 2009; Koster et al., 2009; Seneviratne & Koster, 2012). The length of the dry season may also be increasing in the Amazon (Marengo et al., 2017), and assessing the long-term impacts of such a trend requires multi-depth time series measurements of $\theta_v$. Because soil moisture has a strong effect on forest composition (le Roux, Aalto, & Luoto, 2013), quantifying changes in $\theta_v$ is also important for understanding vegetation succession under changing environmental conditions.

Accurate measurements of $\theta_v$ in old-growth forests are also needed to understand water cycling across the soil–plant–atmosphere system. Infiltration, redistribution, evaporation, transpiration, precipitation recycling, percolation, and groundwater recharge frequently occur simultaneously (Reichardt & Timm, 2012), and reliable $\theta_v$ data in the central Amazon will be critical to validate and benchmark models (Christoffersen et al., 2014; Koyen et al., 2020).

Time domain reflectometry (TDR) is a widely used approach to continuously measure soil moisture, quantified as volumetric water content, $\theta_v$ (Lekshmi, Singh, & Baghini, 2014). Time domain reflectometry systems measure dielectric permittivity in the soil ($K_a$), which is highly correlated to water content (Capparelli, Spolverino, & Greco, 2018; Robinson, Gardner, & Cooper, 1999). This relationship is typically not significantly affected by soil temperature, which helps enable robust measurements of $\theta_v$ (Dasberg & Dalton, 1985; Topp, Davis, & Annan, 1980). In the central Amazon, TDR measurements have frequently used calibrations developed from agricultural soils (Broedel et al., 2017; Teixeira, 2001) or directly applied the Topp model (Topp et al., 1980) without developing the recommended site-specific calibrations. However, agriculture alters soil properties such as structure and bulk density, which result in lower percolation compared with old-growth forest soils. Furthermore, studies have shown that the Topp model (Topp et al., 1980) can be particularly problematic for tropical soils. In tropical soil characteristics such as Fe oxide content, particle size distribution (texture) and organic matter content can cause the $K_a$–$\theta_v$ relationship to differ significantly from the Topp model (Bruno et al., 2006; Kaiser, Reinert, Reichert, & Minella, 2010; Madeiros, Castro, Goldenfum, & Clarke, 2007; Roth, Malicki, & Plagge, 1992; Teixeira, 2001; Teixiera, Schroth, Marques, & Huwe, 2003; Tommasselli & Bacchi, 2001; Weitz, Grauel, Keller, & Veldkamp, 1997). These studies point to the need for a site-specific TDR calibration for old-growth forest soils in the central Amazon.

In this study, our objectives are (a) to develop a site-specific TDR calibration for the central Amazon, (b) to quantiﬁcate the magnitude of deviation of the $K_a$–$\theta_v$ relationship between the site-speciﬁc calibration and the Topp model, and how that changes through the soil proﬁle, (c) to understand how soil moisture varies within the soil proﬁle due to changes in soil characteristics, and (d) to determine the dynamics of soil moisture during seasonal wet and dry periods. Deep soil moisture data are quite rare in the humid tropics, and these data are insightful for understanding how soil texture and stratigraphy, precipitation, and vegetation water use drive temporal variations in soil moisture. This study helps demonstrate that accurate soil moisture measurements are critical for improving understanding water dynamics in the Amazon and to benchmark land surface models.

## 2 | MATERIALS AND METHODS

### 2.1 | Site description

The study area is located in the Tropical Silviculture Experimental Station (EEST, per its acronym in Portuguese, also known as ZF2) located at (2.45–2.66° S, 60.02–60.32° W), 53 km north of the city of Manaus, Amazonas, Brazil, in the central Amazon (Figure 1a). The EEST encompasses 21,000 ha, most of which is old-growth forest (Andrade & Higuchi, 2009). The topography of the region is characterized by a sequence of plateaus, slopes, and valleys (Ferraz, Oht, & Salles, 1998). In the EEST, plateaus vary from 90 to 105 m asl, and small valleys vary from 45 to 55 m asl (Ferraz et al., 1998; Renno et al., 2008). The climate of the region is tropical monsoon (Am) in the Köppen classification (RADAMBRASIL, 1978). Our study area is characterized by a mean annual temperature of 27 °C and mean annual rainfall of 2365 mm, with the dry season (rainfall < 100 mm mo⁻¹; Sombroek, 2001) from July to September (Negrón-Juárez et al., 2017), and annual mean relative humidity of 84% (Leopoldo, Franken, Salati, & Ribeiro, 1987).
FIGURE 1 Study area. (a) Location of the pits at the Tropical Silviculture Experimental Station (EEST, also known as ZF2, red contour) near the city of Manaus in the central Amazon, Brazil; (b) installation of soil water sensor at 1.5 m inside the wall using a custom-designed device; (c) sensor installed at 1.5 m inside the wall; and (d) pit face after sensor installation. The South America image is from Blue Marble (https://visibleearth.nasa.gov/), and the background image is from Google Earth Pro.

The soil types are closely related to topography and can be classified into three main types: Yellow Latossol on the plateaus, Red-Yellow Podzolic on the slopes, and hydro-morphic sandy soils in the valleys (Ferraz et al., 1998). Soil texture, organic matter content, soil moisture, soil pH, and soil C and N concentrations vary significantly along topographic gradients in the central Amazon (Luizao et al., 2004). On the plateaus, soils are derived from tertiary sediments of the Barreiras Group and are dominated by kaolinite, quartz, iron oxides and hydroxides, and Al (Chauvel et al., 1992). These soils are clay rich (Broedel et al., 2017). Clay contents are 65–75% in the upper 30 cm of the soil profile and reach 80–90% in the 2- to 4-m layer. By 15 m, clay contents slowly decrease to 57%. The soil is typically poor in P, Ca, Mg, and K (Teixeira, Schroth, Marques, & Huwe, 2014) but at the same time supports a highly productive forest due to multiple P-uptake strategies like investment in fine roots (Lugli et al., 2019). The upper 50 cm has the highest concentrations of organic matter of ~15 Mg C ha⁻¹, and by 80 cm, it decreases to ~2.5 Mg C ha⁻¹ (Marques et al., 2015). Broedel et al. (2017) found that porosity varies from 60.6 to 58.5% at 80 cm and from 49.8 to 47.4% at 14.2 m.

The vegetation is upland old-growth forest (Ferreira, Luizao, & Dallarosa, 2005) characterized by a high diversity of tree species (Carneiro et al., 2005; Higuchi et al., 1997; Saito, Sakai, Nakamura, & Higuchi, 2003), with a mean canopy height of ~30 m and the tallest trees exceeding 40 m (Lima, Teixeira, Carneiro, Santos, & Higuchi, 2007). Lecythidaceae, Sapotaceae, Fabaceae, Chrysobalanaceae, Burseraceae, Annonaceae, Moraceae, and Euphorbiaceae are the most abundant botanical families in the EEST (Carneiro et al., 2005; Higuchi et al., 1997; Saito et al., 2003; Vieira et al., 2004). Some of the most common species that characterize the area are *Dinizia excelsa* Ducke (angelim-pedra), *Eschweilera coriacea* (DC.) S.A. Mori (mata matá), *Protium apiculatum* Swart (breu-vermelho), *Scleronema micranthum* (Ducke) Ducke (cardeiro), and *Micrandropsis scleroxylon* (W.A. Rodrigues) W.A. Rodrigues (piãozinho) (Carneiro et al., 2005; Higuchi et al., 2004; Vieira et al., 2004). The mean density of stems with DBH (diameter at breast height) ≥ 10 cm is 584.3 ± 25.9 trees ha⁻¹ (da Silva et al., 2002; Vieira et al., 2004), with an annual mortality rate of 8.7 trees ha⁻¹ (Higuchi et al., 1997).
2.2 | Deep pit and soil moisture sensors

A deep pit was used in this study to obtain soil samples and to perform measurements of soil moisture. The pit is located on a plateau centered at 2.6099°S and 60.2093°W, ∼15 m from the K34 eddy flux tower (de Araujo et al., 2002), and has dimensions of 1.2-m length × 1.8-m width × 17-m depth (hereafter referred to as the deep pit). The deep pit is managed by the Large Scale Biosphere-Atmosphere experiment in the Amazon (LBA)/Hydrology Group at the Brazil’s National Institute for Amazonian Research (INPA). The deep pit was dug in 2001 as part of the Ecocarbon project from LBA (Avissar, Dias, Díaz, & Nobre, 2002; Keller, Bustamante, Gash, & Silva Dias, 2009), and observations of soil moisture were started in the pit in 2003. All walls of the deep pit are covered with hard transparent plastic for protection, and the pit opening is sealed with a door. The pit is equipped with a ladder structure and underground access platforms and ventilation system, which allows technicians to descend with safety. Since the installation of the pit, there were no changes in the experimental site, since it is a protected reserve. The deep pit surroundings are covered with intact tropical forest. Between 2014 and 2018, the sensors installed in the pit stopped working and data were not recorded. The pit was closed and remained isolated. During this period, the pit did not suffer any damage such as wall collapse or lateral leakage. The pit was retrofitted in 2014 as part of the GoAmazon project (Martin et al., 2017). In our research area, previous studies have measured soil texture, porosity, macroporosity, microporosity, soil density (Broede et al., 2017), root distribution (Chauvel et al., 1992), and hydraulic conductivity (on disturbed soils near Manaus) (Teixeira et al., 2014; Tomasella & Hodnett, 1996). No stones are present in the soils and most roots are near the surface (<0.5 m), with their distribution declining rapidly with depth (Chauvel et al., 1992; Cordeiro et al., 2020; Marques et al., 2015). Bedrock and groundwater at the site are quite deep, and the bottom of the pit is many meters above groundwater and the bedrock interface.

In 2018 and as part of the NGEE-Tropics project, TDR CS655 (Campbell Scientific) sensors were installed horizontally in the north pit wall at 0.8-, 1.6-, 2.4-, 3.2-, 4.8-, 6.4-, 8.8-, and 14.20-m depths (details in Section 2.4). Due to the structural design of the deep pit, it was not possible to install sensors shallower than 0.8 m. Therefore, a second shallow pit was constructed near the deep pit, and CS655 TDR sensors were installed at 0.025-, 0.05-, 0.15-, 0.30-, 0.50-m depths. Measurements were initiated in July 2018, and logging was conducted on 30-min intervals using a CR1000x datalogger (Campbell Scientific). Measurements reported here are from September 2018 (to allow for equilibration after installation) to January 2020. Electrical problems resulted in missing data from 11 to 19 Sept. 2019.

The CS655 sensors operate under the TDR principle. The sensors have two parallel 12-cm-long stainless-steel rods that form an open-ended transmission line in which the wave propagation velocity depends upon the dielectric permittivity of the medium surrounding the rods. A differential oscillator circuit is connected to the two rods, with an oscillator state change triggered by the return of a reflected signal from one of the rods and the two-way travel time of the wave varies with the dielectric permittivity ($K_a$) that, in turn, depends largely on soil water content (Campbell Scientific, 2018). The volumetric water content is frequently calculated from $K_a$ using the Topp model (Topp et al., 1980), although site-specific calibrations should be used as explained below. Further details on the CS655 sensors can be found in the sensor manual available on the Campbell Scientific homepage (https://www.campbellsci.com/).

2.3 | Soil moisture calibration

To test soil moisture calibration approaches, we collected soil samples from the deep pit at the same eight depths where the sensors were installed using a 10-cm-diam. soil sampling auger to collect bulk soil samples 1 m horizontally from the north pit face. Soil samples were placed into plastic bags, sealed, and transported to the laboratory. After this procedure, bulk density samples were collected using 98-cm³-diam. Kopecky rings of (DIK-1801, Daiki Rika Kogyo Company). At each of the eight horizontal depths, three replicate bulk density sampling rings were collected (24 samples total). The rings were pressed into the soil, carefully excavated, cleaned to remove excess soil, and then immediately wrapped in plastic film. Additional soil samples were collected at each depth with the auger (~10 cm horizontally) to determine the maximum rooting depth of live roots. Live roots were distinguished from dead roots based on their brighter color, stiffness and turgidity, and tightly adhered cortex and periderm. Dead roots were mushy or desiccated and brittle, easily broken or separated, and darker brown or black in color. Only one sample per depth was used to determine the presence of roots.

To calculate the field gravimetric water contents and bulk densities to determine volumetric water contents, the 24 Kopecky ring samples were first weighed with an analytical balance with 0.001-g precision (AD 330, Marte Scientific) to determine wet mass ($m_{wet}$). The samples were then oven dried at 105 °C for 48 h, which is recommended for tropical organic soils (ASTM, 2014; O’Kelly & Sivakumar, 2014). After oven drying, the mass of dry soil was determined. Soil bulk density was then calculated based
on dry soil per unit volume (\(m_{\text{dry}}\)). The gravimetric water content, \(\theta_g\), was calculated as

\[
\theta_g = \frac{(m_{\text{wet}} - m_{\text{dry}})}{m_{\text{dry}}}
\]  

(1)

Volumetric water content was calculated as

\[
\theta_v = \frac{(m^3 \text{ m}^{-3})}{\rho_{\text{bulk}}} = \theta_g \rho_{\text{bulk}}
\]  

(2)

where \(\rho_{\text{bulk}} = m_{\text{dry}}/\text{volume}_{\text{Kopecky}}, \) and \(\text{volume}_{\text{Kopecky}} = 98 \text{ cm}^3\).

Supplemental Table S1 provides details about the undisturbed soil samples. Soil samples collected for TDR calibration were homogenized following methods developed by the Brazilian Agricultural Research Corporation (EMBRAPA; Donagema, Campos, Calderano, Teixeira, & Viana, 2011). The bulk soil samples were crushed and air dried for 2 wk in a room conditioned with continuous dry air to lower water contents to residual water content levels. The air-dried samples were sieved (2-mm mesh, Telas MM) to produce air-dried fine soil (ADFS; Donagema et al., 2011).

To develop data for TDR calibration, we followed the recommendations of the manufacturer for the model CS655 sensors (Campbell Scientific, 2018). Pairs of short and long cylindrical PVC (polyvinyl chloride) were filled with soil to determine if there were soil volume effects on the calibration measurements. The two cylinders were filled with soils collected from each target sensor depth in the pit. Both cylinders had 20-cm internal diameters, the short ones were 22 cm long, and the longer ones were 37 cm long. Both cylinders were larger than the minimum recommended soil radius around (>7.5 cm) and below (>4.5 cm) each TDR rod following Campbell Scientific (2018). The amount of soil used in each cylinder was fixed and determined by obtaining the apparent density of the field conditions. Prior to calibrations, the soil was rehydrated by placing samples in a 50-L container and carefully mixed with sequentially increasing of water (0, 5, 10, 15, 20, 25, 30, and 40%). The wet soil was then packed into the cylinders to the bulk density observed in the field (see Section 3). The TDR probe rods were then carefully inserted in the cylinders, and measurements of \(K_a\) were initiated after a ~1- to 2-min period to allow for sensor stability. The measurements were collected using a datalogger model CR800 (Campbell Scientific). Each TDR sensor was calibrated by making \(K_a\) measurements for multiple water contents for the appropriate soil from the depth where the sensor would be installed. To verify water contents, one sample was collected from each cylinder using Kopecky rings for calculating volumetric water contents using gravimetric water contents and bulk densities as described in Equations 1 and 2. Calibration calculations are discussed in Section 2.5 below.

2.4 Field sensor installation

After calibration, each TDR sensor was installed inside the pit wall at the same locations that were used to collect the respective calibration soil for each sensor (one TDR per soil depth). To minimize edge effects of the pit, sensors were installed 1.5 m into the pit wall using a custom-made device (Figure 1b). This device makes two small pilot holes (with a slightly smaller diameter than the sensor rods to assure good soil contact, Figure 1c), and then the sensor was pushed into place. After installation, the holes were backfilled with the previously removed soil from the same depth as the sensor was calibrated (Figure 1d).

2.5 Calibration calculations using local soils

The \(K_a\) values from the short and long cylinders were similar (<2% difference) for a given water content and soil (i.e., no volume effects were observed), and therefore all the data were used to establishing \(K_a - \theta_v\) relationships for the local soil calibration. \(K_a\) values were used to obtain the calibrated model of the volumetric water content (\(\theta_v\)) using a third degree polynomial \((\theta_v = aK_a + bK_a^2 + cK_a^3 + d)\), where \(a, b, c,\) and \(d\) are coefficients), which was solved using SigmaPlot 11 software (Systat Software). The standard error (\(\sigma_{\text{std}} = \sqrt{\sigma^2} = \sqrt{\sum (y - y')^2/(N - 1)}\) of the fit was calculated where \(y\) and \(y'\) are the observed and predicted values, respectively, and \(N\) is the number of data (Wilks, 2006). The \(N\) was 128 (eight depths, eight moisture increments, two pots). The SEs of the coefficients (Wilks, 2006) of the fit were also calculated. To compare measured \(\theta_v\) values with values using the Topp model \((\theta_v^{\text{Topp}})\), we calculated: \((\theta_v - \theta_v^{\text{Topp}}) \times 100/\theta_v\) (%).

2.6 Independent soil moisture data for validation

In order to further validate the laboratory TDR calibrations, we leveraged a complementary study of upper soil \(\theta_v\) that used frequency domain capacitance (FDC) probes installed ~40 m to the south of the deep pit, on the opposite side and slightly downslope from the K34 tower (G. Spanner, personal communication, 2020). The FDC probes (EnviroSCAN, Sentek) were installed into PVC access tubes to a depth of 1 m, and \(\theta_v\) was measured at 10-, 20-, 30-, 40-, 50-, 70-, and 100-cm depths. The FDC probes had been calibrated in air and under water, and a site-specific calibration was developed by sampling soil adjacent to one of the access tubes. On 17 Oct. 2018, 5-cm-tall metal Kopecky
FIGURE 2  Calibrated model (black line) between observed volumetric water content ($\theta_{v\text{,obs}}$) and the dielectric constant $K_a$: volumetric water content ($\theta_v$, m$^3$ m$^{-3}$) = $-(0.088 \pm SE_1) + (5.7 \pm SE_2) \times 10^{-2} K_a - (2 \pm SE_3) \times 10^{-1} K_a^2 + (2.912 \pm SE_4) \times 10^{-5} K_a^3$ ($p < .0001$, $r^2 = .96$, adjusted $r^2 = .96$). SE$_1$ = 0.021, SE$_2$ = 0.4, SE$_3$ = 0.03, SE$_4$ = 0.445. Curves were fitted using statistical package of SigmaPlot 11 (Systat Software). The volumetric water content obtained from the Topp model ($\theta_v = -5.3 \times 10^{-2} + 2.92 \times 10^{-2} K_a - 5.5 \times 10^{-4} K_a^2 + 4.3 \times 10^{-6} K_a^3$) (Topp et al., 1980) is also shown. (b) Comparison of the difference between the calibrated and Topp model with respect to the observations. The colors of the symbols correspond to depths shown in Panel a. Conf, 95% confidence band; Pred, 95% prediction band.

Rings were used to sample soil carefully along the side of the PVC access pipe, using two samples per depth. The $\theta_v$ was calculated as described in Equations 1 and 2 for each Kopecky ring, and then the resulting values were compared with the in situ sensor-based FDC estimate of $\theta_v$ measured at the time the Kopecky rings were sampled. A linear regression between FDC-derived $\theta_v$ and Kopecky measurements was used to develop the site-specific calibration. Subsequently, the shallow CS655 (TDR) measurements were compared with the simultaneous FDC-based $\theta_v$ measurements for the same depths.

2.7 Rainfall data

Thirty-minute data of accumulated rainfall for the same period of measurements of soil moisture were obtained from the EEST pluviometer network (available at http://lba2.inpa.gov.br/hidrologia/index.php/edicao-atual). Data were collected using a TB4 tipping bucket rain gauge (Hydrological Services America) located at 2.6090 °S and 60.2133 °W, a few meters from the deep pit.

2.8 Data archive

Quality assurance and quality controlled soil moisture and precipitation data were archived following protocols designed by the NGEE-Tropics project and available at https://ngee-tropics.lbl.gov/. Calibrated soil moisture and rainfall data used in this study can be accessed at https://doi.org/10.15486/ngt/1602141.

3 RESULTS

Bulk densities and live root depths from the deep pit were important for calculations of volumetric water contents and for describing conditions within the pit (see Section 4). Soil bulk densities for the eight deep pit depths (from top to bottom) were 1.17, 1.14, 1.20, 1.14, 1.11, 1.30, 1.32 g cm$^{-3}$ (Supplemental Table S1) and varied with pit soil stratigraphy described in Chauvel et al. (1992) and Broedel et al. (2017). Live roots were found to a depth of 10 m, but not below. A comparison of the local soil calibration and the Topp model is shown in Figure 2, along with the actual measured calibration values. The local soil calibration represented the observed $K_a-\theta_v$ relation well (black line in Figure 2; $p < .0001$, $r^2 = .96$, $\sigma_{est} = 0.03$), but the Topp model did not. The Topp model reveals a consistent underestimation of water contents (gray line in Figure 2a). Figure 2b shows that for all depths, the calibrated model was closer to observations than the Topp model. It is also noted that for depths >3.2 m, the calibrated model
produced large errors for soil moisture $< 0.2 \text{ m}^3 \text{ m}^{-3}$. This will be addressed in Section 4. Differences between the soil moisture derived using the Topp model and the calibration data are plotted in Figure 3 and show that the Topp model underestimates $\theta_v$ across the whole range of $K_s$. The average underestimation was $28 \pm 5\%$ (mean $\pm$ SD) and was largest for low soil moisture values (42% for $\theta_v = 0.25 \text{ m}^3 \text{ m}^{-3}$). Even at higher soil water content, the underestimation was never below 22%.

The data from Figure 2 suggest that the local soil-based calibration provides a substantially better representation of soil moisture than the Topp model. To further test the representativeness of the calibrated data, we compared our results with measurements from the FDC sensor (Figure 4). We emphasize that TDRs and FDC sensors were in different locations (FDC sensors installed 1 m from trees, with site-specific differences, and root and macropores differences), and the FDC sensor integrates its signal against a different volume of soil than the TDR probe. In addition, differential disturbance by insect or animal fauna in the upper soil near measurements contribute to spatial variations in $\theta_v$ and could also influence both the FDC $\theta_v$ and TDR $\theta_v$ measurements. Indeed, there was evidence of several voids around the FDC access tube during calibrations that prevented use of the samples from those locations. Despite these issues, the TDR and FDC agreed fairly well, particularly for the 30- and 50-cm layers where FDC $\theta_v$ overlapped with TDR $\theta_v$.

The variability of rainfall and $\theta_v$ through the entire depth profile with time is shown in Figure 5. From the soil surface to $\sim 2.5$ m, $\theta_v$ responded quickly to precipitation events and dry downs during periods with little to no precipitation. Below 2.5 m, $\theta_v$ did not exhibit the same strong dry down periods as the shallower soil zone, although percolation events associated with high precipitation periods were observable to 8 m. Deep percolation events occurred on 7 Nov. 2018, 13 Dec. 2018, and 9 Jan. 2019, for example, and rain events of 10 mm or larger are, in general, correlated with these events. However, antecedent moisture contents and frequency of precipitation events also appear to be important controls on deep percolation. The 6- to 7-m zone consistently had the highest $\theta_v$ values of all the
approach provided a much more realistic estimate of $\theta_v$ than the Topp model (Topp et al., 1980) for the soils at our study site. The Topp model yielded systematically low values, and the magnitude of the differences from independently measured, laboratory-based water contents were substantial (Figure 3). Maximum deviations occurred at the highest water contents. Caldwell, Bongiovanni, Cosh, Halley, and Young (2018) also found greater deviations at higher water contents for their batch equilibration calibration analyses using the Topp model, although the overall shape of the measured $K_s-\theta_v$ relation for their study soils was quite different from that in this study.

Although the Topp model can be satisfactorily applied for some soils, our results suggest that this model should not be assumed as representative for clay-rich humid tropical soils without verification. There are a few likely reasons why the third-degree polynomial fit using local soils differs from the Topp model for the study site soils. Bulk densities from the pit produced a polynomial with coefficients of an order of magnitude different than similar bulk densities used by Topp et al. (1980). Soil texture (i.e., high clay contents at the study site) and structure in our site (discussed in Broeck et al., 2017; Marques et al., 2015) are likely reasons for the deviation. High-clay-content soils can cause dispersive waveforms because of high surface areas, which create bound water effects. Dispersive behavior causes permittivity to be out of phase across the TDR frequency bandwidth (Robinson, Jones, Wraith, Or, & Friedman, 2003).

The local soil calibration for the pit soils resulted in a distinctive $K_s-\theta_v$ relation (Figure 2). For $\theta_v \leq 0.3$ m$^{-3}$ m$^{-3}$, the $K_s-\theta_v$ slope is quite steep. The high slope may be related to the stronger matric suctions associated with drier soils (matric potential decrease and strong pressures bind water to the soil) and residual water content effects (especially for the lowest part of the calibration curve), which can affect the electric field applied by the sensor (Bonan, 2016; de Jeu, Holmes, Parinussa, & Owe, 2014; Wang & Schmugge, 1980). Over the range of $\theta_v$ between $\sim 0.3$ and $\sim 0.5$ m$^3$ m$^{-3}$, the curve has a lower slope where $K_s$ increases more rapidly with a given change in $\theta_v$. For $\theta_v \geq 0.5$ m$^3$ m$^{-3}$, the slope increases again as the volumetric water content approaches the porosity of soil (Wang, Schmugge, & Williams, 1978). Figure 2b shows that the calibrated model produced large errors for depth $> 3.2$ m when $\theta_v < 0.2$ m$^3$ m$^{-3}$, yet these laboratory-created soil moisture values (for our calibration) were never observed in the field for those depths (Figure 5).

4 | DISCUSSION

4.1 | Soil moisture calibration

Given the need for accurate $\theta_v$ measurements, this study examined the effect of calibration on TDR based measurements. We found that a local soil-based calibration approach provided a more realistic estimate of $\theta_v$ than the Topp model (Topp et al., 1980) for the soils at our study site. The Topp model yielded systematically low values, and the magnitude of the differences from independently measured, laboratory-based water contents were substantial (Figure 3). Maximum deviations occurred at the highest water contents. Caldwell, Bongiovanni, Cosh, Halley, and Young (2018) also found greater deviations at higher water contents for their batch equilibration calibration analyses using the Topp model, although the overall shape of the measured $K_s-\theta_v$ relation for their study soils was quite different from that in this study.

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4.2 | Soil moisture dynamics

Temporal and depth variability of $\theta_v$ at the study site from 10 Sept. to 22 Oct. 2018 revealed that moisture content
profiles within the relationship during the dry period, where there is a was 1992 and 2017 dynamics ∼ values occur between 3 and 2017 values (light to dark blue to light blue transitions in 2017 data from January 2003 to January 2006. NEGRÓN-JUÁREZ et al. (2017) examined θv profiles within the same pit using θv data from January 2003 to January 2006. They showed that observed depth variability in θv was largely related to changes in soil texture and structure (including macroporosity), and root density. This study extends the work of Broedel et al. (2017) in some key ways, beyond the benefit of having an additional set of data from a later time period. First, Broedel et al. (2017) did not use a local soil calibration in an old-growth forest but a calibration developed from soil moisture observation up to 1.5 m over monoculture and agroforestry systems in the central Amazon (Teixeira, 2001). Second, Broedel et al. (2017) did not make TDR measurements shallower than 80 cm (although some shallow data were measured nearby using a neutron probe). As shown in Figures 5 and 6 (and discussed below), with respect to Broedel et al. (2017), this study was able to examine higher frequency θv dynamics with better depth resolution in the shallow soils where root densities are highest. Finally, the data from this study provided a higher resolution view of the temporal variability across the entire soil profile, which revealed features and characteristics that were not observed in the Broedel et al. (2017) dataset. For example, the details of pulsed percolation events are much more evident in the newer dataset. This difference is likely related to the Kν−θv relationship developed in this study that revealed finer scale differences, as well as improvements in the TDR sensors.

The following discusses the key characteristics of each depth zone. Seasonal soil moisture decline during the dry season and recovery after rainfall events were readily observed in the upper two soil zones, but their dynamics differ, likely due to the textural differences and the decline in root biomass with depth. In the upper ∼2.5-m zone, the effects of dry down are clearly seen by the low θv contents in Figure 5 during the dry season (e.g., September and October of 2018). The dry down was most pronounced in the upper 0.5- to 1-m depths. The 2018 dry season decrease in moisture at shallow depths was largely driven by plant water use because there was little rainfall to replenish soil water storage, and soil evaporation has been shown to be only a minor part of the site water balance (Broedel et al., 2017; Negrón-Juárez et al., 2007). Root density is also substantially higher in the upper 0.5 m than at deeper depths (Chauvel et al., 1992). Although preferential flow was not measured in this study, measurements from a site in central Amazonia (Tomasella & Hodnett, 1996) showed that macropores in the Manaus clayey soils are concentrated in the first 0.75 m of the soil profile and decrease abruptly at 1.2 m deep, concomitant with the reduction of root density. The effect of macropores can be clearly seen in Figure 5 during the dry period, where there is a layer at ∼0.5 m that drains rapidly after rainfall events and remains drier than contiguous layers. Additional discussion of dry period effects on shallow soil moisture is provided below. When the wet season began in late 2018, water contents increased in the shallow zone, and by December, water contents had increased substantially. Multiple percolation pulses can be seen in the shallow soils during the wet season (blue vertical streaks in Figure 5) resulting from large individual storms and the combination with elevated antecedent moisture conditions. Soil structure and macroporosity likely play an important role in terms of infiltration and percolation in the shallow zone, which has a strongly structured microaggregate characteristic (Chauvel et al., 1992) and higher macroporosity (Broedel et al., 2017) than the deeper soil zones. These features promote rapid infiltration and percolation, resulting in little to no overland runoff at the site despite the large amounts of rainfall.

In the intermediate zone (∼2.5 to ∼8 m), soil moisture is more consistent with time, and during the dry season there are only small drawdown effects (consistent with a substantial reduction in root density). Within this zone, there are depth intervals with distinctly higher or lower θv values (light to dark blue to light blue transitions in Figure 5). Consistently high θv values occur between 3 and 4 m and between 5 and 7 m (especially between about 6 and 6.5 m). Differences in water content in these intervals are related to soil texture and structure, and root densities. The microaggregate structure becomes less pronounced with depth in this zone, with a major transition to substantially less structure at ∼3.5 m. There is also an increase in porosity at ∼6.5 m (Broedel et al., 2017; Chauvel et al., 1992; Chauvel, Lucas, & Boulet, 1987), which corresponds to a zone of continuously elevated moisture content. Some fine roots are present in this zone, and it appears that plants can utilize this water during drought periods, although little to no plant water uptake from this zone appears to occur during nonextreme drought periods (Broedel et al., 2017), which was the situation during this study. In contrast with the shallow soils with strong transpiration-driven dry down periods, temporal variability in this intermediate zone appears to be largely controlled by wet season percolation events (Figure 5). The bottom of
this layer at ∼8 m appears to be the lowest depth where deep pulsed percolation events have a substantial impact on temporal variability of θ_v. It is also notable that the duration of these distinct pulses (based on the width of the dark blue vertical “spikes” in Figure 5) is only a few days, indicating that redistribution of these relatively deep water additions happens rapidly until about the 6.5-m depth.

In the upper part of the lower zone (∼8–12 m), θ_v is typically lower than that at the bottom of the intermediate zone (6–8 m) and below that water contents increase again. Porosity is lower compared with the intermediate zone, and Broedel et al. (2017) suggested that deep percolation was the main control on θ_v in the deep zone. Our survey of living roots indicated that there were none below 10 m, which supports the idea of drainage as opposed to evapotranspiration as the major control in this zone. In general, the strong temporal variations that are apparent in the upper and intermediate zones are substantially damped in the lower zone. However, there was an increase in water content to saturation or near-saturation levels starting in very late December 2018 at ∼14 m that appears to be related to percolation of wet season rainfall. The elevated θ_v values at 14 m persisted for >3 mo into April 2019. This event lagged the initial wet up in the shallow and intermediate zones by >1 mo, which gives an indication of the time needed for water to percolate from the intermediate zone to 14 m. Recharge to the groundwater table at 30–35 m typically occurs ∼4 mo after onset of the wet season (Tomasella et al., 2008).

A higher resolution time series of the variations in θ_v over most of the 2018 dry season is shown in Figure 6, and it shows quite interesting dynamics during a 21-d period when plant available water was most limited during the study. At shallow depths (<2.5 m), θ_v values have high temporal variability, whereas deeper depths show minimal variability. As mentioned in Section 3, the shallow time series have three main characteristics: (a) a distinct dry down trend until the rain events in late October; (b) rapid but short-duration increases in θ_v in response to infrequent rain events; and (c) diurnal fluctuations in θ_v.

The dry down period reduced θ_v at 0.05 m from ∼0.4 to ∼0.27 m³ m⁻³ over a 40-d period, which included rain events on seven different days (Figure 6). The extent of the dry down decreased with depth and by 3.2 m was barely detectible. The larger dry downs in the top 0.5 m are consistent with the highest root densities observed in the pit (Chauvel et al., 1992), and based on the overall moisture profiles, it appears that plant water uptake was dominantly in the upper 0.5 m with minor uptake down to ∼3.2 m. However, during drought events, water uptake might occur from very deep soils (Markewitz, Devine, Davidson, Brando, & Nepstad, 2010) Percolation depths inferred by increases in θ_v during and after rain events were primarily limited to the upper 0.5 m, although the 1.6-m sensor did show some rain-event-related increases. The deeper parts of the profile do not show any increases in θ_v over the same period, so deep percolation was minimal. Overall, these results suggest that plant water availability was sufficient in the shallower depths to meet transpiration demand. Infrequent rains helped buffer stores of shallow plant available water, and it would be interesting to see if deeper water stores would be accessed if rainfall amounts and frequency were reduced during drought conditions. Continued monitoring at the site will help clarify patterns of θ_v, and plant water use over interannual periods (Bruno et al., 2006).

The shallower θ_v profiles show distinct diurnal variations with higher water contents occurring during the night and early morning period, and lower water contents during the afternoon and early evening. Diurnal characteristics with each sensor depth down to 2.4 m are summarized in Table 1, and results were determined using the average θ_v of each daily maximum and minimum for a given depth. The times of the daily minima and maxima were also examined. Only rain-free days were used in the summary, although lingering rainfall effects from the relatively infrequent rains likely account for some of the variability between depths. These were small amplitude diurnal changes in θ_v, where percentage differences (difference between maximum and minimum/maximum × 100) was ∼2% or less (Table 1). Decreases in amplitude with depth are clearly evident from the percentage difference between maximum and minimum data in Table 1, and by 2.4-m depth, there was only occasional diurnal variability. Temporally, the average maximum θ_v values typically occurred between midnight and 0300 h, and there was no clear trend with depth. Average minimum values occurred in the afternoons to early evenings between about 1400 and 2000 h. Average durations between maximum and minimum θ_v values ranged from 15 to 19 h. The diurnal pattern is common during the dry season, as shown in Figure 6. However, it is not apparent during the wet season (see Supplemental Figure S1), suggesting that the observed pattern is not an artifact (seasonal temperatures are very similar; Negrón-Juárez et al., 2017) but a true ecohydrological response.

Diurnal changes in θ_v have been observed in old-growth forests in the eastern Amazon, Brazil (da Lopes, 2001; da Rocha et al., 2004). Diurnal variations observed at the Tapajos field site by da Rocha et al. (2004) extended down to 2-m depth, and daily variations were a few percent at 0.05 m and decreased in amplitude with depth down to 2 m. They showed a similar timing of peak θ_v at night, like in this study; however, daily minima appear to have occurred by 1200 h or earlier based on Figure 3 of their manuscript, a substantially shorter duration between
TABLE 1  Summary of 2018 dry-season diurnal variability of volumetric water content ($\theta_v$) with depth. Average values are from 10 Sept. to 24 Oct. 2018. Only rain-free days were included in the calculations

| Depth | Avg. min. $\theta_v$ | SD min. $\theta_v$ | Avg. max. $\theta_v$ | SD max. $\theta_v$ | Max.–min. difference | Avg. max. time | Avg. min. time | Avg. duration max. to min. |
|-------|----------------------|-------------------|----------------------|-------------------|-----------------------|----------------|---------------|--------------------------|
| m     | m$^{-3}$             | m$^{-3}$          | m$^{-3}$             | m$^{-3}$          | %                     | h:min          | h             | h                        |
| 0.05  | 0.3022               | 0.00036           | 0.3096               | 0.00042           | 2.2                   | 2:39           | 17:58         | 15                       |
| 0.15  | 0.3313               | 0.00023           | 0.3369               | 0.00028           | 1.6                   | 0:38           | 19:03         | 18                       |
| 0.3   | 0.4233               | 0.00026           | 0.4276               | 0.00027           | 1.0                   | 0:44           | 19:44         | 19                       |
| 0.5   | 0.3753               | 0.00027           | 0.3789               | 0.00028           | 0.9                   | 0:25           | 19:20         | 16                       |
| 1.6   | 0.4426               | 0.00013           | 0.4442               | 0.00013           | 0.3                   | 2:21           | 17:01         | 15                       |
| 2.4   | 0.4434               | 0.00005           | 0.4438               | 0.00005           | 0.1                   | 1:28           | 13:48         | 12                       |

minima and maxima than we observed. They attributed the nocturnal recovery in $\theta_v$ to either hydraulic lift within the plant root system or flow through the bulk soil (presumably related to the physical processes discussed above). Oliveira, Dawson, Burgess, and Nepstad (2005) measured sap flow on roots at the same site, which suggested upward movement of water in tap roots and release to the soil along lateral roots during the dry season, consistent with the concept of hydraulic lift and hydraulic redistribution. They also noted downward movement of water through roots during the wet season, which bypassed some soil depths, creating near-instantaneous increases of water to depths well below that which could be accounted for by simple percolation. We observed similar bypassing during the wet season, although given the lack of root sap flow data it is not clear if the bypassing is related to downward redistribution within the roots or preferential or macropore flow effects, which could result in similar behaviors. A detailed examination of the diurnal variations using the deep pit data is underway and will be the subject of a future study.

5 CONCLUSIONS

This study provides the first TDR soil moisture calibration ($\theta_v$) in an old-growth forest in the central Amazon. A calibration based on local soil measurements found that the Topp et al. (1980) model underestimated the soil moisture content by 22–42%. This large difference suggests that site-specific calibration of TDR sensors for tropical soils are necessary, especially in soils with high clay contents as observed in plateau areas in the central Amazon. Using the improved calibration, we were able to examine temporal $\theta_v$ dynamics down to 14.2 m. Seasonal and subdaily variations in $\theta_v$ were observed, with the greatest temporal variability occurring in the top soil layer. A strong dry season reduction in $\theta_v$ was limited to the top 2.4 m, suggesting that this was the zone of greatest plant water use. Although minor decreases in $\theta_v$ were observed for the deeper depths during the dry season, pulsed deep percolation events appear to be responsible for much of the temporal variability in the deeper soil. Continued monitoring at the site will provide a better understanding of interannual soil water dynamics in the central Amazon and will be extremely valuable for characterizing future drought impacts in old-growth forests.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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REFERENCES

Andrade, E. A., & Higuchi, N. (2009). Productivity of four Terra Firme tree species of central Amazonia. (In Portuguese, with English abstract.) Acta Amazonica, 39, 105–112. https://doi.org/10.1590/S0044-59672009000100011
ASTM. (2014). *Standard test methods for moisture, ash, and organic matter of peat and other organic soils*. ASTM International. Retrieved from https://compass.astm.org/download/D2974.23152.pdf

Austin, A. T., Yahdjian, L., Stark, J. M., Belnap, J., Porporato, A., Horton, U., … Schaeffer, S. M. (2004). Water pulses and biogeochemical cycles in arid and semiarid ecosystems. *Oecologia*, 141, 221–235. https://doi.org/10.1007/s00442-004-1519-1

Avisar, R., Dias, P. L. S., Dias, M., & Nobre, C. (2002). The Large-Scale Biosphere-Atmosphere Experiment in Amazonia (LBA): Insights and future research needs. *Journal of Geophysical Research-Atmospheres*, 107(D20). https://doi.org/10.1029/2002jd002704

Bonan, G. (2016). *Ecological climatology: Concepts and applications* (3rd ed.). Cambridge, UK: Cambridge University Press.

Brocca, L., Morbidelli, R., Melone, F., & Moramarco, T. (2007). Soil moisture spatial variability in experimental areas of central Italy. *Journal of Hydrology*, 333, 356–373. https://doi.org/10.1016/j.jhydrol.2006.09.004

Broedel, E., Tomasella, J., Candido, L. A., & von Randow, C. (2017). Deep soil water dynamics in an undisturbed primary forest in central Amazonia: Differences between normal years and the 2005 drought. *Hydrological Processes*, 31, 1749–1759. https://doi.org/10.1002/hyp.11143

Bruno, R. D., da Rocha, H. R., de Freitas, H. C., Goulden, M. L., & Miller, S. D. (2006). Soil moisture dynamics in an eastern Amazonian tropical forest. *Hydrological Processes*, 20, 2477–2489. https://doi.org/10.1002/hyp.6211

Caldwell, T. G., Bongiovanni, T., Cosh, M. H., Halley, C., & Young, M. (2014). Deep soil water dynamics in an undisturbed primary forest in central Amazonia. *Hydrological Processes*, 31, 1749–1759. https://doi.org/10.1002/hyp.11143

Campbell Scientific. (2018). CS650 and CS655 water content reflectometers. Logan, UT: Campbell Scientific. Retrieved from https://dx.campbellsci.com/documents/us/manuals/cs650.pdf

Capparelli, G., Spolverino, G., & Greco, R. (2018). Experimental determination of TDR calibration relationship for pyroclastic ashes of Campania (Italy). *Sensors*, 18(11). https://doi.org/10.3390/s18113727

Carneiro, V. M. C., Lima, A. J. N., Pinto, A. C., Santos, J., Teixeira, L. M., & Higuchi, N. (2005). Floristic composition and structural analysis of terra firme forests in Manaus, Amazonas, Brazil. In *V Congresso Florestal Nacional: A Floresta e as Gentes* (pp. 1–12). Viseu, Portugal: Actas das Comunicações–Inventário, Modelação e Gestão.

Chauvel, A., Lucas, Y., & Boulet, R. (1987). On the genesis of the soil mantle of the region of Manaus, central Amazonia. *Brazilian Journal of Meteorology*, 43, 234–241. https://doi.org/10.1007/bf01945546

Chauvel, A., Vital, A. R., Lucas, Y., Desjardins, T., Franken, W. K., Luizao, F. J., … Bedmar, A. P. (1992). *Proceedings of the VII Brazilian Conference of Meteorology*. São Paulo: Brazilian Meteorological Society.

Christoffersen, B. O., Restrepo-Coupe, N., Arain, M. A., Baker, I. T., Cestaro, B. P., Ciais, P., … Saleska, S. R. (2014). Mechanisms of water supply and vegetation demand govern the seasonality and magnitude of evapotranspiration in Amazonia and Cerrado. *Agricultural and Forest Meteorology*, 191, 33–50. https://doi.org/10.1016/j.agrformet.2014.02.008

Cordeiro, A., Norby, R., Andersen, K., Valverde-Barrantes, O., Fuchsleger, L., Oblitas, E., … Quesada, C. A. (2020). Fine-root dynamics vary with soil depth and precipitation in a low-nutrient tropical forest in the central Amazonia. *Plant-Environment Interactions*, 1, 3–16. https://doi.org/10.1002/pei3.10010

da Lopes, J. L. (2001). Soil moisture observations in pasture and forest areas in Rondonia using frequency domain reflectometry. (In Portuguese.) São Paulo, Brazil: University of Sao Paulo.

da Rocha, H. R., Goulden, M. L., Miller, S. D., Menton, M. C., Pinto, L., de Freitas, H. C., & Figueira, A. (2004). Seasonality of water and heat fluxes over a tropical forest in eastern Amazonia. *Ecological Applications*, 14, S22–S32. https://doi.org/10.1890/02-6001

da Silva, R. P., dos Santos, J., Tribuzy, E. S., Chambers, J. Q., Nakamura, S., & Higuchi, N. (2002). Diameter increment and growth patterns for individual tree growing in central Amazon, Brazil. *Forest Ecology and Management*, 166, 295–301. https://doi.org/10.1016/S0378-1127(01)00678-8

Dasberg, S., & Dalton, F. N. (1985). Time domain reflectometry field measurements of soil-water content and electrical-conductivity. *Soil Science Society of America Journal*, 49, 293–297. https://doi.org/10.2136/sssaj1985.03615995004900020003x

de Araujo, A. C., Nobre, A. D., Krujit, B., Elbers, J. A., Dallarosa, R., Stefani, P., … Kabat, P. (2002). Comparative measurements of carbon dioxide fluxes from two nearby towers in a central Amazonian rainforest: The Manaus LBA site. *Journal of Geophysical Research-Atmospheres*, 107(D20). https://doi.org/10.1029/2001jd000676

de Jeu, R. A. M., Holmes, T. R. H., Parinussa, R. M., & Owe, M. (2014). A spatially coherent global soil moisture product with improved temporal resolution. *Journal of Hydrology*, 516, 284–296. https://doi.org/10.1016/j.jhydrol.2014.02.015

Dirmeyer, P. A., Schlosser, C. A., & Brubaker, K. L. (2009). Precipitation, recycling, and land memory: An integrated analysis. *Journal of Hydrometeorology*, 10, 278–288. https://doi.org/10.1175/2008jh1016.1

Donagema, G. K., de Campos, D. V., Calderano, S. B., Teixeira, W. G., & Viana, J. H. (2011). *Manual of soil analysis methods*. Rio de Janeiro, Brazil: EMBRAPA.

Dorigo, W. A., Wagner, W., Hohensinn, R., Hahn, S., Paulik, C., Xaver, A., … Jackson, T. (2011). The International Soil Moisture Network: A data hosting facility for global in situ soil moisture measurements. *Hydrology and Earth System Sciences*, 15, 1675–1698. https://doi.org/10.5194/hess-15-1675-2011

Eltahir, E. A. B. (1998). A soil moisture rainfall feedback mechanism I: Theory and observations. *Water Resources Research*, 34, 765–776. https://doi.org/10.1029/97wr03499

Famiglietti, J. S., Devereaux, J. A., Laymon, C. A., Tsegaye, T., Houser, P. R., Jackson, T. J., & van Oevelen, P. J. (1999). Ground-based investigation of soil moisture variability within remote sensing footprints during the Southern Great Plains 1997 (SGP97) Hydrology Experiment. *Water Resources Research*, 35, 1839–1851. https://doi.org/10.1029/1999wr900047

Ferraz, J., Oht, S., & Salles, P. C. (1998). Distribuição dos solos ao longo de dois transectos em floresta primária ao norte de Manaus (AM). In N. Higuchi, M. A. A. Campos, P. T. B. Sampaio, & J. Santos (Eds.), *Pesquisas Florestais para a Conservação da Floresta e Reabilitação de Áreas Degradadas da Amazônia* (pp. 111–143). Manaus, Brazil: National Institute for Amazon Researches (INPA).

Ferreira, S. J., Luizao, F., & Dallarosa, R. (2005). Throughfall and rainfall interception by an upland forest submitted to...
selective logging in Central Amazonia. *Acta Amazonica*, 35, 55–62. https://doi.org/10.1590/S0044-59672005000100009

Fontes, C. G., Dawson, T. E., Jardine, K., McDowell, N., Gimenez, B. O., Anderegg, L., … Chambers, J. Q. (2018). Dry and hot: The hydraulic consequences of a climate change-type drought for Amazonian trees. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 373(1760). https://doi.org/10.1098/rstb.2018.0209

Gimenez, B. O., Jardine, K. J., Higuchi, N., Negron-Juarez, R. I., Sampao, I. D., Cobello, L. O., … Chambers, J. Q. (2019). Species-specific shifts in diurnal sap velocity dynamics and hysteretic behavior of ecophysiological variables during the 2015-2016 El Nino event in the Amazon Forest. *Frontiers in Plant Science*, 10. https://doi.org/10.3389/fpls.2019.00830

Higuchi, N., Chambers, J. Q., Santos, J., Ribeiro, R. J., Pinto, A. C., Silva, R. P., … Tribuzy, E. S. (2004). Carbon balance and dynamics of primary vegetation in the central Amazon. *Floresta*, 34, 295–304.

Higuchi, N., Dos Santos, J., Ribeiro, R. J., Freitas, J. V., Vieira, G., & Cornic, A. (1997). *Proceedings of the Biomass and Nutrients International Symposium*. Manaus, Brazil: National Institute for Amazonian Research (INPA).

Kaiser, D. R., Reinert, D. J., Reichert, J. M., & Minella, J. P. G. (2010). Dielectric constant obtained from TDR And volumetric moisture of soils in southern Brazil. *Revista Brasileira De Ciencia Do Solo*, 34, 649–658. https://doi.org/10.1590/S0100-06832010000300006

Keller, M., Bustamante, M., Gash, J., & Silva Dias, P., (Eds.). (2009). *Amazonia and global change*. Washington, DC: American Geophysical Union. https://doi.org/10.1029/GM186

Koster, R. D., Dirmeyer, P. A., Guo, Z. C., Bonan, G., Chan, E., Cox, P., … Team, G. (2004). Regions of strong coupling between soil moisture and precipitation. *Science*, 305, 1138–1140. https://doi.org/10.1126/science.1100217

Koster, R. D., Guo, Z. C., Yang, R. Q., Dirmeyer, P. A., Mitchell, K., & Puma, M. J. (2009). On the nature of soil moisture in land surface models. *Journal of Climate*, 22, 4322–4335. https://doi.org/10.1175/2009jcli2833.1

Koyen, C. D., Knox, R. G., Fisher, R. A., Chambers, J. Q., Christophersen, B. O., Davies, S. J., … Xu, C. G. (2020). Benchmarking and parameter sensitivity of physiological and vegetation dynamics using the Functionally Assembled Terrestrial Ecosystem Simulator (FATES) at Barro Colorado Island, Panama. *Biogeoosciences*, 17, 3017–3044. https://doi.org/10.5194/bg-17-3017-2020

Kunert, N., Aparecido, L. M. T., Wolff, S., Higuchi, N., dos Santos, J., de Araujo, A. C., & Trumbore, S. (2017). A revised hydrological model for the Central Amazon: The importance of emergent canopy trees in the forest water budget. *Agricultural and Forest Meteorology*, 239, 47–57. https://doi.org/10.1016/j.agrformet.2017.03.002

le Roux, P. C., Aalto, J., & Luoto, M. (2013). Soil moisture’s underestimated role in climate change impact modelling in low-energy systems. *Global Change Biology*, 19(10). https://doi.org/10.1111/gcb.12286

Lei, F. N., Crow, W. T., Holmes, T. R. H., Hain, C., & Anderson, M. C. (2018). Global investigation of soil moisture and latent heat flux coupling strength. *Water Resources Research*, 54, 8196–8215. https://doi.org/10.1029/2018wr023469

Lekshmi, S. U. S., Singh, D. N., & Baghini, M. S. (2014). A critical review of soil moisture measurement. *Measurement*, 54, 92–105. https://doi.org/10.1016/j.measurement.2014.04.007

Leopoldo, P. R., Franken, W., Salati, E., & Ribeiro, M. N. (1987). Towards a water-balance in the central Amazonian region. *Experientia*, 43, 222–233. https://doi.org/10.1007/bf01945545

Lima, A. J. N., Teixeira, L. M., Carneiro, V. M. C., Santos, J., & Higuchi, N. (2007). Biomass stock and structural analysis of a secondary forest in Manaus (AM) region, ten years after clear cutting followed by fire. *Acta Amazonica*, 37, 49–54.

Lugli, L. F., Andersen, K. M., Aragao, L. E., Cordeiro, A. L., Cunha, H. F., Fuchslueger, L., … Hartley, I. P. (2019). Multiple phosphorus acquisition strategies adopted by fine roots in low-fertility soils in central Amazonia. *Plant Soil*, 450, 49–63. https://doi.org/10.1007/s11104-019-03963-9

Luizao, R. C. C., Luizao, F. J., Paiva, R. Q., Monteiro, T. F., Sousa, L. S., & Krujit, B. (2004). Variation of carbon and nitrogen cycling processes along a topographic gradient in a central Amazonian forest. *Global Change Biology*, 10, 592–600. https://doi.org/10.1111/j.1529-8817.2003.00757.x

Madeiros, J., Castro, N., Goldenfum, J., & Clarke, R. T. (2007). TDR calibration in a latosol soil. *Brazilian Journal of Water Resources*, 12, 19–25.

Marengo, J. A., Fisch, G. F., Alves, L. M., Sousa, N. V., Fu, R., & Zhuang, Y. Z. (2017). Meteorological context of the onset and end of the rainy season in central Amazonia during the GoAmazon2014/5. *Atmospheric Chemistry and Physics*, 17, 7671–7681. https://doi.org/10.5194/acp-17-7671-2017

Markewitz, D., Devine, S., Davidson, E. A., Brando, P., & Nepstad, D. C. (2010). Soil moisture depletion under simulated drought in the Amazon: Impacts on deep root uptake. *New Phytologist*, 187, 592–607. https://doi.org/10.1111/j.1469-8137.2010.03991.x

Marques, J. D., Luizao, F., Teixeira, W., Sarrazin, M., Ferreira, S. J., Beldini, T. P., & Marques, E. M. (2015). Distribution of organic carbon in different soil fractions in ecosystems of central Amazonia. *Revista Brasileira de Ciencia do Solo*, 39, 232–242. http://doi.org/10.1590/01000683rbsc20150142

Martin, S. T., Artaxo, P., Machado, L., Manzi, A. O., Souza, R. A. F., Schumacher, C., … Wendisch, M. (2017). The Green Ocean Amazon Experiment (Goamazon2014/5) observes pollution affecting gases, aerosols, clouds, and rainfall over the rain forest. *Bulletin of the American Meteorological Society*, 98, 981–997. https://doi.org/10.1175/bams-d-15-00221.1

Negrón-Juárez, R. I., Hodnett, M. G., Fu, R., Goulden, M. L., & von Randow, C. (2007). Control of dry season evapotranspiration over the Amazonian forest as inferred from observations at a southern Amazon forest site. *Journal of Climate*, 20, 2827–2839. https://doi.org/10.1175/jcli4184.1

Negrón-Juárez, R. I., Holm, J. A., Magnabosco Marra, D., Rifai, S. W., Riley, W. J., Chambers, J. Q., … Higuchi, N. (2018). Vulnerability of Amazon forests to storm-driven tree mortality. *Environmental Research Letters*, 13(5). https://doi.org/10.1088/1748-9326/aabe9f

Negrón-Juárez, R. I., Jenkins, H. S., Raup, C. F. M., Riley, W. J., Kueppers, L. M., Magnabosco Marra, D., … Higuchi, N. (2017). Windthrow variability in central Amazonia. *Atmosphere*, 8(2). https://doi.org/10.3390/atmos8020028

Negrón-Juárez, R. I., Li, W., Fu, R., Fernandes, K., & Cardoso, A. d. O. (2009). Comparison of precipitation datasets over the tropical South American and African continents. *Journal of Hydrometeorology*, 10, 289–299. https://doi.org/10.1175/2008jhm1023.1

Nepstad, D. C., Decarvalho, C. R., Davidson, E. A., Jipp, P. H., Lefebvre, P. A., Negreiros, G. H., … Vieira, S. (1994). The role of...
deep roots in the hydrological and carbon cycles of Amazonian forests and pastures. Nature, 372, 666–669. https://doi.org/10.1038/372666a0

O’Kelly, B. C., & Sivakumar, V. (2014). Water content determinations for peat and other organic soils using the oven-drying method. Drying Technology, 32, 631–643. https://doi.org/10.1080/07373937.2013.849728

Oliveira, R. S., Dawson, T. E., Burgess, S. S. O., & Nepstad, D. C. (2005). Hydraulic redistribution in three Amazonian trees. Oecologia, 145, 354–363. https://doi.org/10.1007/s00442-005-0108-2

Quesada, C. A., Lloyd, J., Schwarz, M., Patino, S., Baker, T. R., Czimczik, C., … Paiva, R. (2010). Variations in chemical and physical properties of Amazon forest soils in relation to their genesis. Biogeosciences, 7, 1515–1541. https://doi.org/10.5194/bg-7-1515-2010

RADAMBRASIL. (1978). Projeto Radambrasil. Levantamento de recursos naturais. Rio de Janeiro, Brazil: Ministério das Minas e Energia.

Reichardt, K., & Timm, L. C. (2012). Solo, Planta e Atmosfera: Conceitos, Processos e Aplicações. (In Portuguese.) Brasilia: Manole.

Renno, C. D., Nobre, A. D., Cuartas, L. A., Soares, J. V., Hodnett, M. G., Tomasella, J., & Waterloo, M. J. (2008). HAND, a new terrain descriptor using SRTM-DEM: Mapping terra-firme rainforest environments in Amazonia. Remote Sensing of Environment, 112, 3469–3481. https://doi.org/10.1016/j.rse.2008.03.018

Robinson, D. A., Gardner, C. M. K., & Cooper, J. D. (1999). Measurement of relative permittivity in sandy soils using TDR, capacitance and theta probes: Comparison, including the effects of bulk soil electrical conductivity. Journal of Hydrology, 223, 198–211. https://doi.org/10.1016/S0022-1694(99)00121-3

Robinson, D. A., Jones, S. B., Wraith, J. M., Or, D., & Friedman, S. P. (2003). A review of advances in dielectric and electrical conductivity measurement in sods using time domain reflectometry. Vadose Zone Journal, 2, 444–475. https://doi.org/10.2136/vzj2003.0444

Robock, A. (2015). Hydrology, floods and droughts: Soil moisture. In G. R. North, J. Pyle, & F. Zhang (Eds.), Encyclopedia of atmospheric science (2nd ed., pp. 232–239). Cambridge, MA: Academic Press.

Robock, A., Mu, M. Q., Vinnikov, K., Trofimova, I. V., & Adameko, T. I. (2005). Forty-five years of observed soil moisture in the Ukraine: No summer desiccation (yet). Geophysical Research Letters, 32(3). https://doi.org/10.1029/2004GL021914

Robock, A., Vinnikov, K. Y., Srivinasan, G., Entin, J. K., Hollinger, S. E., Speranskaya, N. A., … Namkhai, A. (2000). The global soil moisture data bank. Bulletin of the American Meteorological Society, 81, 1281–1299. https://doi.org/10.1175/1520-0477(2000)081[1281:TSMDBA]2.0.CO;2

Roth, C. H., Malicki, M. A., & Plagge, R. (1992). Empirical-evaluation of the relationship between soil dielectric-constant and volumetric water-content as the basis for calibrating soil-moisture measurements by TDR. Journal of Soil Science, 43, 1–13. https://doi.org/10.1111/j.1365-2389.1992.tb00115.x

Saito, S., Sakai, T., Nakamura, S., & Higuchi, N. (2003). Three types of seedling establishments of tree species in an Amazonian terra-firme forest. In N. Higuchi (Ed.), Projeto Jacaranda Fase II: Pesquisas florestais na Amazonia (pp. 33–41). São José dos Campos, Brazil: Brazilian National Institute for Space Research.

Salati, E., Dalloiso, A., Matsui, E., & Gat, J. R. (1979). Recycling of water in the Amazon basin: Isotopic study. Water Resources Research, 15, 1250–1258. https://doi.org/10.1029/WR015i005p01250

Seneviratne, S. I., & Koster, R. D. (2012). A revised framework for analyzing soil moisture memory in climate data: Derivation and interpretation. Journal of Hydrometeorology, 13, 404–412. https://doi.org/10.1175/jhm-d-11-044.1

Sheffield, J., & Wood, E. F. (2008). Global trends and variability in soil moisture and drought characteristics, 1950–2000, from observation-driven simulations of the terrestrial hydrologic cycle. Journal of Climate, 21, 432–458. https://doi.org/10.1175/2007jcli3822.1

Shuttleworth, W. J. (1988). Evaporation from Amazonian rainforest. Proceedings of the Royal Society Series B: Biological Sciences, 233, 321–346. https://doi.org/10.1098/rspb.1988.0024

Solander, K. C., Newman, B. D., de Araujo, A. C., Barnard, H. R., Berry, Z. C., Bonal, D., … Xu, C. G. (2020). The pantropical response of soil moisture to El Nino. Hydrology and Earth System Sciences, 24, 2303–2322. https://doi.org/10.5194/hess-24-2303-2020

Sombroek, W. (2001). Spatial and temporal patterns of Amazon rain-fall: Consequences for the planning of agricultural occupation and the protection of primary forests. Ambio, 30, 388–396. https://doi.org/10.1639/0044-7747(2001)030[0388:Atapo]2.0.co;2

Teixiera, W. G. (2001). Land use effects on soil physical and hydraulic properties of a clayey Ferralsol in the central Amazon (Vol. 72). Bayreuth, Germany: Institute for Terrestrial Ecosystem Research, University of Bayreuth.

Teixiera, W. G., Schroth, G., Marques, J. D., & Huwe, B. (2003). Sampling and TDR probe insertion in the determination of the volumetric soil water content . Brazilian Journal of Soil Sciences, 27, 575–582. https://doi.org/10.1590/S0100-06832003000400001

Teixiera, W. G., Schroth, G., Marques, J. D., & Huwe, B. (2014). Unsaturated soil hydraulic conductivity in the central Amazon: Field evaluations. In W. G. Teixiera, M. B. Ceddia, M. V. Ottoni, & G. K. Donnagema (Eds.), Application of soil physics in environmental analyses: Measuring, modelling and data integration (pp. 283–305). Cham, Switzerland: Springer. https://doi.org/10.1007/978-3-319-06013-2_13

Ter Steege, H., Pitman, N. C. A., Sabatier, D., Baraloto, C., Salomao, R. P., Guevara, J. E., … Silman, M. R. (2013). Hyperdominance in the Amazonian tree flora. Science, 342(6156). https://doi.org/10.1126/science.1243092

Tomasella, J., & Hodnett, M. G. (1996). Soil hydraulic properties and van Guchen parameters for an Oxisol under pasture in central Amazonia. In J. Gash, C. A. Nobre, J. M. Roberts, & R. L. Victoria (Eds.), Amazonian deforestation and climate (pp. 101–124). Hoboken, NJ: Wiley.

Tomasella, J., Hodnett, M. G., Cuartas, L. A., Nobre, A. D., Waterloo, M. J., & Oliveira, S. M. (2008). The water balance of an Amazonian micro-catchment: The effect of interannual variability of rainfall on hydrological behaviour. Hydrological Processes, 22, 2133–2147. https://doi.org/10.1002/hyp.6813

Tommaselli, J. T., & Bacchi, O. (2001). Calibration of a TDR equipment to moisture measurement in soils. Pesquisa Agropecuária Brasileira, 36, 1145–1154. https://doi.org/10.1590/S0100-204X2001000900008

Topp, G. C., Davis, J. L., & Annan, A. P. (1980). Electromagnetic determination of soil-water content: Measurements in coaxial transmission-lines. Water Resources Research, 16, 574–582. https://doi.org/10.1029/WR016i003p00574
van der Ent, R. J., Savenije, H. H. G., Schaeflie, B., & Steele-Dunne, S. C. (2010). Origin and fate of atmospheric moisture over continents. Water Resources Research, 46(9). https://doi.org/10.1029/2010wr009127

Vieira, S., de Camargo, P. B., Selhorst, D., da Silva, R., Hutyra, L., Chambers, J. Q., ... Martinelli, L. A. (2004). Forest structure and carbon dynamics in Amazonian tropical rain forests. Oecologia, 140, 468–479. https://doi.org/10.1007/s00442-004-1598-z

Wang, J., Schmugge, T. J., & Williams, D. (1978). Dielectric constants of soils at microwave frequencies—II. Washington, DC: NASA.

Wang, J. R., & Schmugge, T. J. (1980). An empirical-model for the complex dielectric permittivity of soils as a function of water-content. IEEE Transactions on Geoscience and Remote Sensing, 18, 288–295. https://doi.org/10.1109/tgrs.1980.350304

Weitz, A. M., Grauel, W. T., Keller, M., & Veldkamp, E. (1997). Calibration of time domain reflectometry technique using undisturbed soil samples from humid tropical soils of volcanic origin. Water Resources Research, 33, 1241–1249. https://doi.org/10.1029/96wr03956

Wilks, D. S. (2006). Statistical methods in the atmospheric sciences (2nd ed). Amsterdam: Elsevier.

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