Research Article

A simple method to determine soil moisture regime for highly weathered tropical soils

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Abstract

Introduction. The soil water balance approach can be used to evaluate soil water dynamics and determine soil moisture regime (SMR) and water availability. Despite some models are available in the literature, they have been validated within temperate regions, and require several input variables, restringing their use when data is limited. **Objective.** To develop a simple method to estimate soil water balance (after infiltration) and further determine the corresponding SMR for highly weathered soils from Costa Rica, Central America. **Materials and methods.** Twelve pedons (distributed in seven regions of Costa Rica) were sampled and described, where monthly total soil available water (TSAW) and available water in the soil control section (AWCS) were calculated. Potential evapotranspiration (ET_o) and monthly dependable precipitation (DP) were estimated using historical data obtained from neighboring meteorological stations. DP, ET_o, TSAW, and AWCS were used as variables in the calculations performed to identify months with soil water deficit. **Results.** Three SMRs were identified: 1) Ustic (six pedons), 2) Udic (four pedons), and 3) Perudic (two pedons). In five assessed pedons, SMR assigned through our soil water balance approach disagreed with that reported in the literature for nearby areas (SMR estimated through Newhall model). However, historical rainfall behavior and the developing crops and vegetation in these regions reinforced the SMR assigned to this research. **Conclusions.** The method developed in the present study was considered satisfactory in determining both soil available water and SMR for highly weathered soils of Costa Rica.

We encourage its use in further studies of hydrology, soil physics, and pedology due to 1) its versatility of use with limited data and 2) the inclusion of meteorological and edaphic variables calibrated under tropical conditions.

Keywords: soil water balance; dependable precipitation; Soil Taxonomy; Ultisols; Oxisols.

Artículo científico

Resumen

Un método sencillo para determinar el régimen de humedad en suelos tropicales altamente meteorizados

Introducción. El balance hídrico se puede utilizar para estimar la dinámica y disponibilidad del agua, así como el régimen de humedad del suelo (SMR). Pese a que en la literatura existen múltiples modelos para determinar este SMR, estos se validaron en regiones templadas y requieren de múltiples variables de entrada, restringiendo su uso en entornos con datos limitados. **Objetivo.** Desarrollar un método simple para estimar el balance hídrico del suelo (después de la infiltración) y determinar el SMR en suelos altamente meteorizados de Costa Rica, América Central. **Materiales y métodos.** Se muestreó un total de doce pedones (distribuidos en siete regiones de Costa Rica) y se calculó su contenido de agua disponible total (TSAW) y en la sección control del suelo (AWCS). A partir de datos obtenidos de estaciones meteorológicas aledañas, se calculó la evapotranspiración potencial (ET_o) y la lluvia confiable (*DP*) mensual. Estas cuatro variables se utilizaron en los cálculos del balance hídrico del suelo para la identificación de los meses con déficit hídrico. **Resultados:** Se identificaron tres SMR: 1) Ústico (seis pedones), 2) Údico (cuatro pedones) y 3) Perúdico (dos pedones). En cinco pedones, el SMR asignado en el presente trabajo presentó diferencias con el reportado en la literatura (estimado mediante el modelo Newhall). Sin embargo, los patrones históricos de precipitación, así como los cultivos y vegetación imperantes en los sitios reforzaron el SMR asignado mediate el enfoque del balance hídrico desarrollado en el presente trabajo. **Conclusiones.** El método desarrollado se consideró satisfactorio en la determinación de la disponibilidad del agua y el SMR en suelos altamente meteorizados de Costa Rica. Se recomienda su uso en futuros estudios de hidrología, física de suelo y pedología, debido a: 1) su versatilidad de uso con datos limitados, 2) incorporación de variables climáticas y edáficas calibradas en condiciones tropicales.

Palabras clave: balance hídrico del suelo; lluvia confiable; taxonomía de suelos; Ultisoles; Oxisoles.

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1. Introduction

Soils are considered a key ecosystem factor due to their functions in the hydrologic cycle, linking energy and water fluxes throughout the soil-plant-atmosphere continuum (Kramer 1969, Andersson *et al.* 2015, Buol *et al.* 2011). Therefore, pedology, hydrology and other emerging sciences like hydropedology are strongly relevant to both agricultural and ecological studies (Buol *et al.* 2011, Lin *et al.* 2006, Lin 2010, Bouma 2012).

Highly weathered soils within the tropical regions are commonly classified according to the system Soil Taxonomy system (Soil Survey Staff 1999) as Ultisols and Oxisols. These soil orders present interesting properties such as the presence of low-activity minerals, high content of fine particles (clay), low water retention and high permeability, in addition to low contents of exchangeable cations and high acidity (West *et al.* 1997, Buol and Eswaran 1999, Camacho *et al.* 2021). In Costa Rica, Ultisols and Oxisols correspond to 43.4% of the total surface area (Mata *et al.* 2020), covering agricultural regions where significant crops such as sugarcane (*Saccharum officinarum* L.), pineapple (*Ananas comosus* (L.). Merr.), or coffee (*Coffea arabiga* L.) represent the main economic activity (Camacho-Umaña *et al.* 2024).

In Soil Taxonomy, there is a fundamental concept denominated soil moisture regimen (SMR), defined as the presence or the absence of water retained within tensions among 33 and 1500 kPa into a specific depth (horizons) and during defined periods of the year (Soil Survey Staff 1999). This SMR is commonly used for suborder designation once taxonomic order has been appropriately identified (Soil Survey Staff 1999, Buol *et al.* 2011), and it takes more importance in agricultural planning and crop establishment according to agroecological interactions, aiming to achieve efficiency in water use and sustainability (Rai and Singh 2012, Lal 2015).

Normally, SMR is determined by estimating the number of days where available water within the soil profile's control section (AWCS) reaches a tension higher than 1500 kPa, but without reaching the "air dry state" (Soil Survey Staff 1999). This determination can be achieved through a soil water balance approach inferred from historic meteorological data (Soil Survey Staff 1999, Tejedor *et al.* 2002, Buol *et al.* 2011, Winzeler *et al.* 2013). In this regard, some models are available in the literature to determine both soil moisture and temperature regime (Newhall 1972, van Wambeke 1987, 2000, Constantini *et al.* 2002, Winzeler *et al.* 2013), which simulates soil moisture behavior under a specific pattern of rainfall, and they are considered accurate for soil taxonomy studies in the United States and Europe.

Models mentioned above use monthly average precipitation (*PM*) inferred from "normal years" as water input (Soil Survey Staff 1999) and potential evapotranspiration (ET_o) as water output. ET_o can be estimated through calibrated equations (Penman 1948, Thornthwaite 1954, Monteith 1965), where many involve several climatic variables (Allen *et al.* 1998). For instance, the Penman-Monteith model is considered as the standard method for evapotranspiration estimating, but its use becomes limited when one or more input

variables are absent. The equation developed by Hargreaves and Samani (1985) to estimate ET_o from temperature and solar radiation values shows good correlation with the models mentioned above (Moeletsi *et al.* 2013) and has been used in soil hydrology studies worldwide (Bautista *et al.* 2009; Gentilucci *et al.* 2021), including specific studies in the tropics (de Sousa Lima *et al.* 2013, Lima Junior *et al.* 2018).

The behavior of the rainfall distribution in moist tropical regions is quite difficult to model and predict due to the influence of ENOS, Atlantic Multi-Decadal Oscillation, and Tropical North Atlantic (Larkin and Harrison 2005, Wolter and Timlin 2011, Maldonado *et al.* 2018). This makes it difficult to achieve the "normal years" condition in *PM* as required by Soil Taxonomy.

Furthermore, van Wambeke (1987) performed a study where SMRs were estimated using the Newhall model (Newhall 1972) for the whole territory of Costa Rica. More recently, Fernández-Moya *et al.* (2014) developed a soil-water balance approach to determine SMR in Andisols from the lands of Guanacaste. However, when carefully assessing these reported SMRs, there are discrepancies among the SMRs assigned with 1) the corresponding historical rainfall patterns and potential soil water availability and 2) the natural vegetation or specific crops developing within their corresponding regions.

Considering all that aforementioned, and particularly this lack of agreement among reported SMR and both: 1) climatic patterns and 2) vegetation, the present study aims to 1) develop a simple method to estimate the soil water balance and 2) determine subsequently the soil moisture regimen for highly weathered soils developed in seven great regions from Costa Rica, Central America.

2. Materials and methods

2.1. Study areas

Seven regions in Costa Rica were selected: a) Mountains of Hojancha, Guanacaste province; b) Mountains of Acosta, in San José; c) Talamanca piedmont at Valle del General and Buenos Aires, located in San José and Puntarenas provinces respectively; d) Mountains of Osa in Puntarenas; e) Lowlands of San Carlos in Alajuela; f) Highlands of Talamanca valley and g) Mountains of Tortuguero, both at Limón province (**Figure 1**). These regions were chosen following two main criteria: a) geological and geomorphological conditions were suitable for well-drained weathered soils development, and b) landscapes were randomly distributed within different climatic regions, aiming to cover as many of the possible scenarios on rainfall patterns as possible (Solano and Villalobos 2001). A review of soil genesis and soil forming factors for the pedons and landscapes are detailed in Camacho *et al.* (2021).
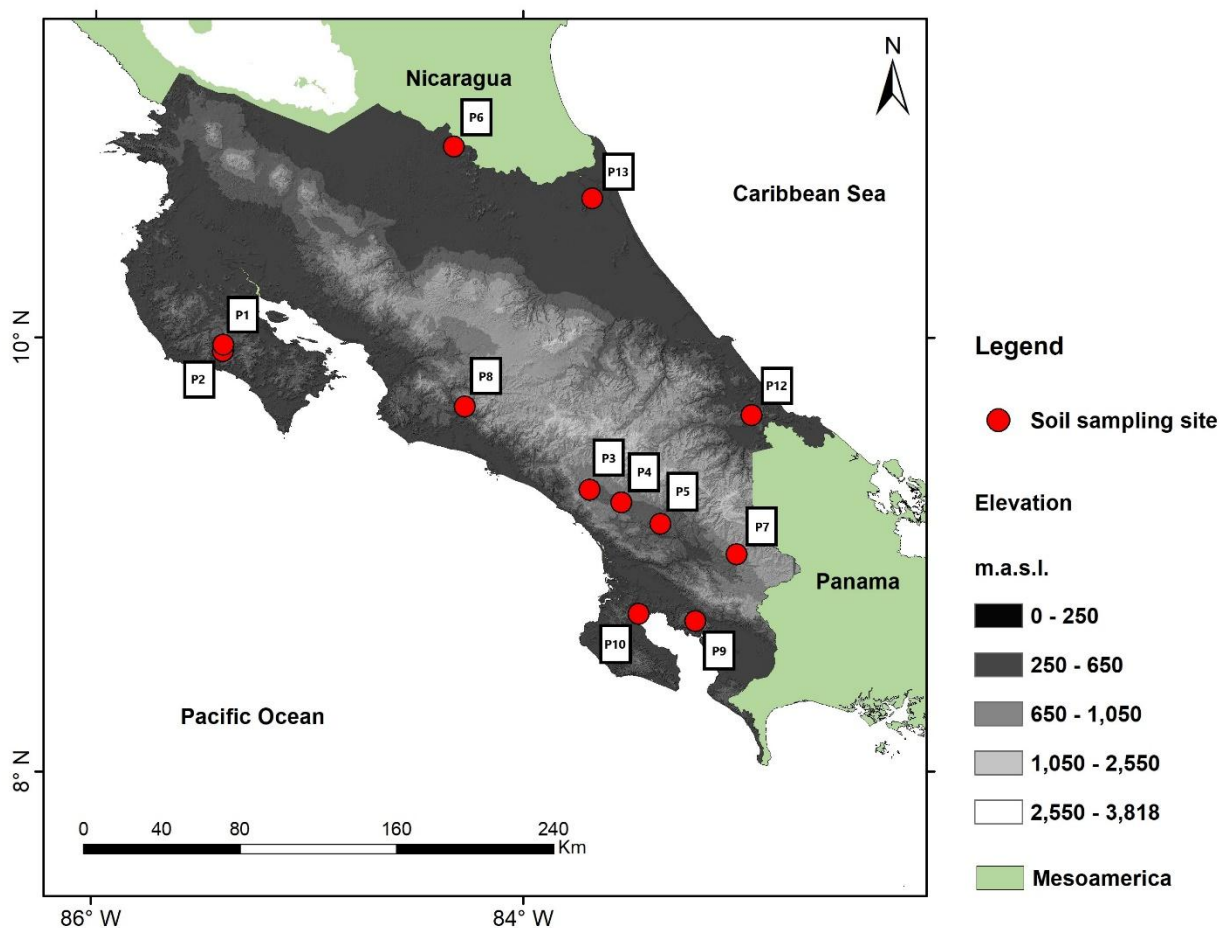
Figure 1. Digital elevation model and geographic localization of 12 pedons sampled and described in present study.
Figura 1. Modelo de elevación digital y localización geográfica de los 12 pedones muestreados y descritos en el presente estudio.

2.2. Soil sampling and data collection

Twelve pedons were sampled and described across Costa Rica (**Figure 1**). Soil descriptions were conducted following Schoeneberger *et al.* (2002). The geographic coordinates, physiography, relief, elevation and slope, soil erosion, apparent fertility, drainage, stoniness, and water table depth were determined for every pedon. In each horizon assessed, moist color was determined following Munsell (1994). Additionally, depth and width, structure features, consistency, pores, roots, and special features were described following Schoeneberger *et al.* (2002).

Soil physical and chemical analyses were conducted at Centro de Investigaciones Agronómicas, University of Costa Rica (hereafter CIA-UCR). Details about the methodologies employed can be easily accessed from Camacho *et al.* (2021).

In summary, soil water retention (SWR) at field capacity (FC at 33 kPa tension) and permanent wilting point (PWP at 1500 kPa tension) for each soil horizon were measured using undisturbed soil cores taken in rings (4.7 cm diameter and 2.54 cm height), using porous ceramic plates and pressure vessels which were set at tension values of 0.33 and 15 bar (33 and 1500 kPa) for FC and PWP, respectively, following the guidelines from Richards (1941), Klute (1986) and Soil Survey Staff (2014a). Particle size distribution analysis (PSDA) was measured using both: 1) pipette methods as described by Soil Survey Staff (2014a) and 2) modified hydrometer method (Gee and Or 2002). Bulk density was accessed through volumetric cylinder following Grossman and Reinsch (2002). Organic carbon contents (OC) were determined by dry combustion (Horneck and Miller 1998).

3. Theory

3.1. Atmospheric water balance

Data (daily minimum, maximum and average air temperature; daily average rainfall and solar radiation) was collected from several meteorological stations (a total of 23) near the soil sampling sites for the climate analysis of the landscapes studied (atmospheric water balance). The data source and the station's features are detailed in **Table 1**. In addition, we consulted data from Handcock and Hargreaves (1977), who analyzed climatic data from 250 meteorological stations along the territory of Costa Rica. Daily potential evapotranspiration (ET_o) was estimated following Hargreaves and Samani (1985):

$$ET_o = 0.0135 \times (T_{med} + 17.78) \times R_s$$

(1)

where ET_o is daily potential evapotranspiration (mm day^{-1}), T_{med} is daily average temperature (°C) and R_s is solar incident radiation (mm day^{-1}). If R_s is not available within the climatic data, Samani (2000) proposed the following equation to calculate R_s from temperature values:

$$R_s = R_0 \times KT \times \sqrt{(T_{max} - T_{min})}$$

(2)

where R_o is sun extraterrestrial radiation (MJ m^{-2} day^{-1}). This R_o comes from tabulated data which values change according to the global position (Allen *et al.* 1998), which is multiplied by 0.408 to convert units to mm day^{-1}; T_{max} and T_{min} are maximum and minimum daily temperature (°C), respectively, and KT is an empirical coefficient. Hargreaves (1994) recommended a $KT = 0.162$ for regions located inland and $KT = 0.19$ for coastal sites.

To calculate potential evapotranspiration (mm) for the *n* month, a sum of daily potential evapotranspiration values (calculated with **equation 1**) was conducted following the equation:

$$ET_{o_n} = \sum_{i=1}^{n} ET_{0_i} = ET_{0_1} + ET_{0_2}.. + ET_{0_d}$$

(3)

where ET_{o_n} is potential evapotranspiration for the *n* month (mm).

Dependable precipitation (*DP*) was estimated from annual precipitations records using the gamma distribution (Husak *et al.* 2007) and a threshold value of 75%, which is precipitation with a 75% probability level of occurrence (Hargreaves 1977). If data is limited to monthly values, *DP* can be calculated from monthly average precipitation values using the equation developed by Hargreaves (1977):

$$DP = 0.77PM - 25$$

(4)

where *DP* is dependable precipitation (mm), and *PM* is monthly average precipitation (mm). Our *DP* values were compared with those reported by Hancock and Hargreaves (1977) for neighboring sites to soils under study, including some of the same meteorological stations used in the present study. Data provided by Hancock and Hargreaves (1977) covered a wide range of years, varying from 25 to 45 years of data registration. Thus, their values can be considered representative and robust.

3.2. Soil water balance after infiltration approach

We propose a simplified method to estimate the soil water balance and soil moisture regime, based on the atmospheric water balance, soil water retention capacity (SWRC), and the water values that enter the soil profile as infiltration. From soil water retention and bulk density data obtained for each soil horizon, water storage capacity was estimated throughout the following equation:

$$\theta_i = \left(w_{fci} - w_{pwpi}\right) \times (\rho_{bi}/\rho_{H_2O}) \times d_i$$

(5)

where θ_i is water storage capacity of the horizon (mm), w_{fci} and w_{pwpi} are gravimetric water content values (g g^{-1}) at field capacity (FC) and permanent wilting point (PWP) respectively; ρ_{bi} is bulk density (g cm^{-3}), ρ_{H2O} is the water density ($\sim$ 1.0 g cm^{-3}) and d_i is the horizon thickness (mm).

Table 1. Meteorological stations and climatic data period consulted for the water balance development.
Tabla 1. Estaciones meteorológicas y periodo de datos consultados para el desarrollo del balance hídrico.

ID number	Name	Latitude North	Longitude West	Elevation (masl)	Data registering period	Source
69551	Guatuso	10° 41'	84° 49'	50	Jan-1996 to Dec-2015	ICE (2015)
69575	Upala	10 ° 54'	85° 01'	50	Jan-1976 to Dec-1994	ICE (2015)
69577	Boca Tapada	10 ° 41'	84° 13'	60	Jan-1976 to Dec-1994	ICE (2015)
69704	Barra del Colorado	10° 46'	83° 35'	5	Jan-2011 to Dec-2014	ICE (2015)
69633	Comando Los Chiles (Automatic)	11° 01'	84° 42'	40	Dic-1994 to Nov-2015	IMN (2015)
69635	Coopevega	10° 43'	84° 24'	100	Sep-1995 to Dec-2015	IMN (2015)
69713	Saint George, Los Chiles (Automatic)	10° 46'	84° 40'	87	Apr-2013 to Nov-2015	IMN (2015)
72105	Colonia Carmona, Nandayure	10° 00'	85°15'	100	Jan-1970 to Jun-1991	IMN (2015)
85012	Hitoi Cerere	09° 40'	83° 01'	100	Jul-1981 to Dec-2015	IMN (2015)
85021	Hitoi Cerere (Automatic)	09° 40'	83° 01'	170	Jun-1995 to Sep-2015	IMN (2015)
87010	Amubri	09° 31'	82° 57'	70	Jan-1996 to Dec-2015	ICE (2015)
87012	Alto Urén	09° 27'	82° 58'	220	Jan-1993 to Dec-2006	ICE (2015)
87014	Alto Lari	09° 23'	83° 02	600	Jan-1994 to Dec-2007	ICE (2015)
87016	Bajo Coen	09°32'	83° 01'	100	Jan-1994 to Dec-2007	ICE (2015)
88005	San Ignacio de Acosta	09°48'	84°10'	860	Jan-1950 to May-1980	IMN (2015)
88045	San Ignacio de Acosta 2	09° 47'	84° 09'	880	Oct-1994 to Dic-2015	IMN (2015)
98066	San Isidro de Biolley	09° 00'	82° 60'	1050	Jan-1996 to Dic-2015	ICE (2015)
98087	Pindeco, Buenos Aires	09° 08'	83° 20'	397	Sep-1995 to Nov-2015	IMN (2015)
nd	Pérez Zeledón	nd	nd	nd	Jan-2010 to Nov-2015	ICAFE (2015)
nd	Hojancha, Guanacaste	nd	nd	nd	Jan-2010 to Nov-2015	ICAFE (2015)
nd	Finca La Ceniza, Pérez Zeledón	09° 18'	83° 41'	754	Jan-2010 to Nov-2015	Coopeagri (2015)
nd	Finca El Porvenir, San Pedro	09° 14'	83° 32'	596	Jan-2010 to Nov-2015	Coopeagri (2015)
nd	Finca El Guayacán, Buenos Aires	09° 08'	83° 21'	380	Jan-2010 to Nov-2015	Coopeagri (2015)

nd: no available data.
m asl: meters above sea level.

To estimate total soil available water (storage capacity), a sum of values of water storage capacity for the horizons calculated with **equation 5** was conducted, following the equation:

$$A = \sum_{i=1}^{n} \theta_i = \theta_1 + \theta_2.. + \theta_n$$

(6)

where A is the total soil water storage capacity (mm).

For the calculus of monthly soil water balance, we assumed a runoff value equivalent to 5% of DP when DP (monthly DP) was higher than 30 mm, in agreement with runoff values obtained from several studies conducted under similar climatic conditions and geomorphologic features within Costa Rica (Harmand *et al.* 2007, Cannavo *et al.* 2011, Villatoro *et al.* 2015).

Then, we assumed an average water value that infiltrates into the soil profile, which was estimated by the following equation:

$$I_n = DP_n - E_n = DP_n - (DP_n \times 0{,}05)$$

(7)

where I_n is the average water content that infiltrated into the soil profile for month n (mm); DP_n is dependable precipitation value for n month (mm) and E_n is average runoff value for n month. Further, we estimate the soil water balance after the infiltration for every evaluated month, through the following equation:

$$B_{at_n} = I_n - ET_{0_n}$$

(8)

where B_{at_n} is soil water balance after infiltration for n month (mm), I_n is the average water content stored into the soil profile for month n (mm) per **equation 7** and ET_{0_n} is potential evapotranspiration for n month estimated with **equation 3**.

From B_{atn} values, a conditional function was established to estimate the number of months where soil total water storage capacity (A) is consumed to the limit as shown by **equation 9**:

$$f(x_n) = \begin{cases} B_{at_n} + B_{at_{n-1}}, & if \ \ A > B_{at_n} + B_{at_{n-1}} > 0 \\ 0, & if \ \ B_{at_n} + B_{at_{n-1}} \leq 0 \\ A, & if \ \ B_{at_n} + B_{at_{n-1}} > A \end{cases}$$

(9)

where $f(x_n)$ is the available water for month n (mm), B_{at_n} is atmospheric water balance on infiltrated soil for n month (mm) and $B_{at_{n-1}}$ is atmospheric water balance on infiltrated soil for previous month (mm). This function begins on the first month of the year where $B_{at_n} \geq A$, that means the month where pedon is virtually wet. Then, this function is applied until obtaining a complete year (12 months).

This last calculus normalizes soil water content because 1) soil can't hold more water than *A*, and 2) negative values of $B_{at_n} + B_{at_{n-1}}$ correspond to water deficit (soil available water decreased).

A second calculus with **equation 9** was performed to estimate SMR but substituting the *A* value by the available water on soil pedon control section (AWCS). According to Soil Survey Staff (1999), the moisture control section of a given soil extended from 10 to 30 cm below the soil surface if the particle-size class of the soil is fine-loamy, coarse-silty, fine-silty, or clayey. This last one (clayey) was the dominant textural class within the pedons assessed in the present research, with clay values of 40 - 64% for A_p and 44 - 79% for B_t horizons (Camacho *et al.* 2021).

Therefore, the AWCS was estimated per **equations 5** and **6** for each pedon but using the corresponding horizons which were sampled and described within 10 and 30 cm depth, and considering the thickness d_i, following the guidelines from Soil Survey Staff (1999) for clayey soils.

3.3. Soil limited data and pedotransfer functions as an alternative for SWR inputs

Aiming to extend the scope of soil water balance after infiltration in further studies using this simple method to other soils with limited data (e.g. soil profiles without measured SWR values), pedotransfer functions (PTFs) available on software Rosetta1 (Schaap *et al.* 2001) were used to estimate fit parameters for the van Genuchten model (van Genuchten 1980). This model describes the water retention function that describes the relation between the soil water content (θ_h) and its corresponding soil water potential (*h*):

$$\theta_h = \begin{cases} \theta_r + \dfrac{\theta_s - \theta_r}{[1 + |\alpha h^n|]^m} & , h < 0 \\ \theta_s & , h \geq 0 \end{cases} \tag{10}$$

where θ_s and θ_r are the saturated and residual water contents ($L^3 \ L^{-3}$), respectively; α (L^{-1}) and *n* (unitless) are empirical fitting parameters; *m* is related to *n* by $m = 1 - 1/n$ (unitless), and h is the tension value (cm H_2O). The parameters θ_s, θ_r, α, and n were estimated for each soil horizon assessed using Rosetta1, which calculates these fit parameters from the corresponding particle size distribution analysis (PSDA), bulk density and organic carbon content (OC). More details about the PTFs and corresponding methodologies employed can be easily accessed from Schaap *et al*. (2001).

Once fit parameters were obtained for each soil horizon, soil water content for field capacity (FC) and permanent wilting point (PWP) was calculated through **equation 10**, setting *h* values of 336.5 and 15295.74 cm H_2O, respectively.

Because the van Genuchten's model calculates directly volumetric water content (θ), water storage capacity of the horizon (l_i) was estimated with a modification of **equation 6**:

$$l_i = \left(\theta_{fci} - \theta_{pwpi}\right) \times d_i$$

(11)

where θ_{fci} and θ_{pwpi} are volumetric water content values at field capacity (FC) and permanent wilting point (PWP) respectively; and d_i is the corresponding horizon thickness (mm).

The calculated water content values at FC and PWP were compared with their corresponding measured values through single linear regression analysis, aiming to evaluate the performance of pedotransfer equations. Regression analyses were performed on R Studio® (R version 4.3.0 (2023-04-21) "Already Tomorrow") using the *glm* procedure (RStudio Team 2015).

3.4. Soil moisture regime assignment (SMR)

After the soil water balance approach was completed for each pedon, the number of days for months where AWCS was totally depleted were computed, and further SMR was assigned following the guidelines of Soil Survey Staff (1999). A summary of the description of soil moisture regimes (reported in Costa Rica) is detailed on **Table 2**.

Soil moisture regimes assigned for pedons assessed in the present study were compared with those previously assigned for Costa Rica by van Wambeke (1987) through: 1) the spatial location of current pedons within the soil moisture regimes distribution map adapted from van Wambeke (1987), and 2) comparing soil moisture regime reported for climatologic stations nearby the pedon sampling points in Costa Rica. After soil moisture regimen was determined for each pedon assessed, soils were classified to the Taxonomic Subgroup level following guidelines from the last edition of Keys to Soil Taxonomy (Soil Survey Staff 2014b).

4. Results

4.1. Soil water content and pedotransfer functions performance

Low values of available water ($\theta_{fc} - \theta_{pwp}$) were found for all horizons studied (n = 57), with a range between 0.04 and 0.13 cm^3 cm^{-3} (**Figure 2A**). Consequently, we observed low values for both total soil (TSAW) and available water in the control section (AWCS) for the twelve pedons assessed, where AWCS estimates were relatively lower than 50 mm (**Figure 2B**), which is a fixed value used in the Newhall model and Soil Survey Staff (2014b) for estimating soil moisture regime (SMR).

Soil volumetric water content values at FC and PWP calculated through the van Genuchten's equation (using pedotransfer functions) for soil horizons presented a strong relation with those directly measured from soil samples (R^2 values of 0.92 and 0.89, respectively). Despite this behavior, the RMSE values estimated for FC and PWP were 0.11 and 0.07 cm^3 cm^{-3}, respectively, which suggest considerable differences (higher than 0.05 cm^3 cm^{-3}) between measured and predicted values. Notoriously, the volumetric water content values calculated for FC and PWP were lower than those directly measured (**Figure 3A**). Conversely, the available water values calculated with Rosetta® were higher than those directly measured from soil samples (**Figure 3B**). These same values presented a lower relationship with those directly measured ($R^2 = 0.60$), with a RMSE value of 0.04 cm^3 cm^{-3}.

Our data suggested that pedotransfer equations used in the present study (Rosetta1®) to estimate water content at field capacity and permanent wilting point underestimated the water content at both hydrological reference values (FC and PWP) and overestimated the available water by about 24% when compared with the measured values (**Figure 3B**)

4.2. Soil water balance after infiltration estimated for highly weathered soils

The results obtained with this proposed water balance approach for the twelve pedons assessed are detailed in **Figures 4** and **5**. We included the atmospheric water balance (*ET_o* vs *DP*) and the associated total soil available water (TSAW). While assessing pedons P1 and P2 (Mountains of Hojancha) the values of dependable precipitation (*DP*) and potential evapotranspiration (*ET_o*) indicate eight months (November - May, and July) where atmospheric water balance is negative (*ET_o* > *DP*), modifying water input and its corresponding soil water stored during the year (**Figure 4 A** and **B**). A bimodal rainfall pattern caused by a short drought period in July, which added to maximum rainfall values in September and October, limited the TSAW to 5 months, then seven months where soil profiles present water deficit.

Similar behavior was found in the landscape Talamanca Piedmont landscape which is oriented to Valle del General (**Figure 4 C, D** and **E**), where negative atmospheric water balance extended for just five months (December - April), conditioning water availability for pedons studied. In this regard, pedon P3 showed a deficit of water available for four months (January-April), while in pedons P4 and P5 the water deficit extended to five months (December - April). High rainfall values allow water availability during seven and eight months of the year (**Figure 4 C, D** and **E**).

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Table 2. Description of soil moisture regimes (SMR) reported in soils of Costa Rica.
Tabla 2. Descripción de los regímenes de humedad del suelo (SMR) reportados en suelos de Costa Rica.

Soil moisture regime	Main characteristics
Aquic	Soil is virtually out of oxygen due to saturation.
	Soil remains saturated for some period of the year, during normal years. Evidence of chemical reduction.
Perudic	Soil presents a hydric surplus for 12 months ($ET_0 < PM^*$) in the control section.
	Soil does not get dry during no period of the year.
Udic	Soil presents a hydric surplus ($ET_0 < PM^*$) for 90 cumulative days or even more in the control section.
	Soil dries for a period shorter than 90 cumulative days of the year.
Ustic	Soil presents a hydric deficit ($ET_0 > PM^*$) for 90 cumulative days or even more in the control section.
	Soil dries for a period longer than 90 cumulative days of the year and gets moist during 180 cumulative days or 90 consecutive days per year.

*PM: Monthly mean precipitation inferred from normal years (Soil Survey Staff 1999).
All this information was adapted from Alvarado (1985), Soil Survey Staff (1999) and Boul *et al.* (2011).
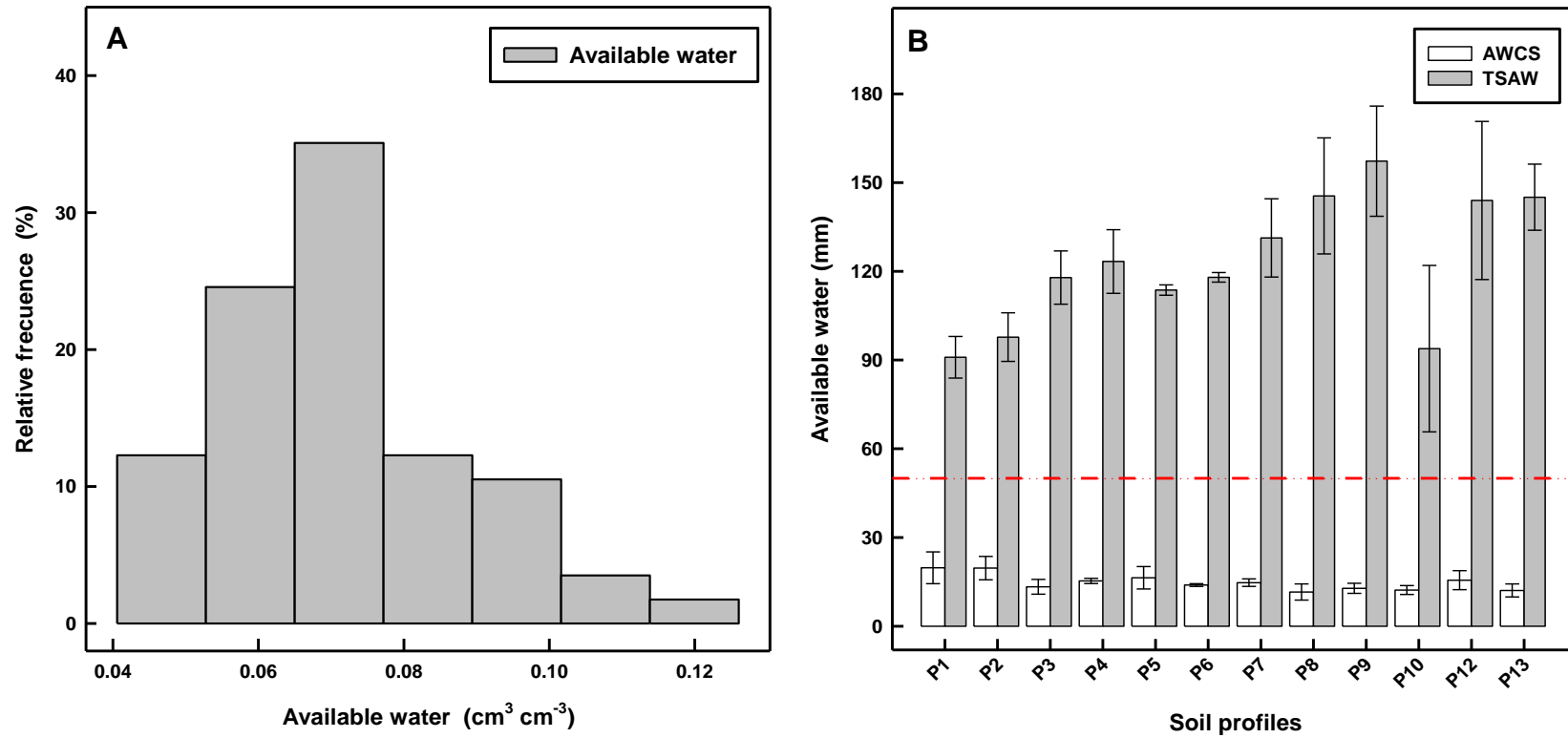
Figure 2. Relative frequency of available water values measured from soil horizons sampled (A) and calculated total soil available water (TSAW) and available water in the control section (AWCS) for twelve pedons assessed in present study (B). Error bars represent 95% confidence interval. Discontinuous red line denotes 50 mm as AWCS as suggested by van Wambeke (1987) and Soil Survey Staff (1999).

Figura 2. Frecuencia relativa de los valores de agua disponible medidos en los horizontes del suelo muestreados (A) y valores calculados de contenido total de agua disponible del suelo (TSAW) y agua disponible en la sección de control (AWCS) para doce pedones evaluados en el presente estudio (B). Las barras de error representan el intervalo de confianza del 95%. La línea roja discontinua indica 50 mm como AWCS, según lo sugerido por van Wambeke (1987) y Soil Survey Staff (1999).
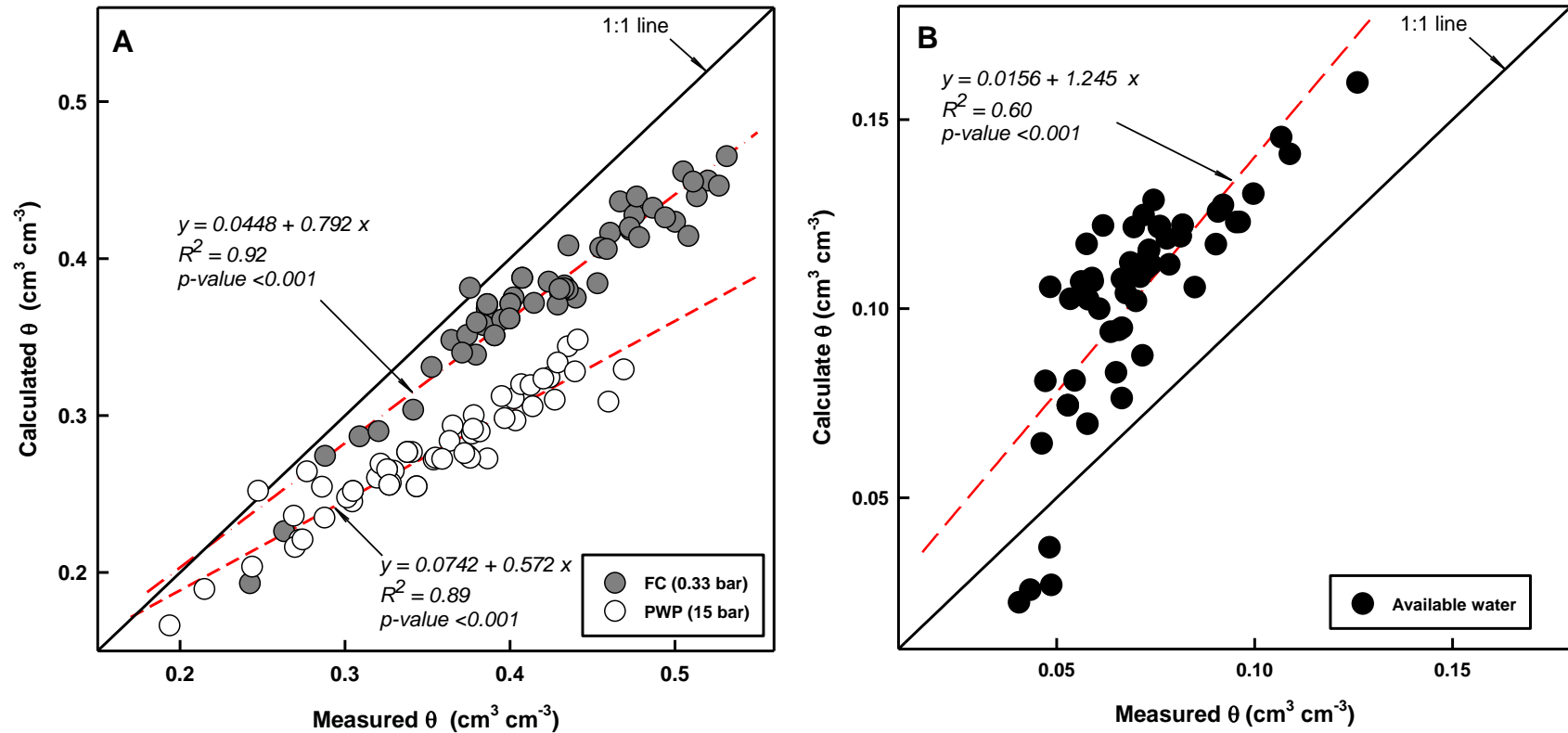
Figure 3. Calculated volumetric moisture values at field capacity (FC) and permanent wilting point (PWP) (A) and, available water (B) plotted against measured values for horizons sampled on twelve soil pedons assessed on present study. Red lines indicate fitted linear regression models. Calculated values for FC and PWP were estimated through van Genuchten equation (van Genuchten 1980), using fitting parameters obtained through Rosetta1 (Schaap *et al.* 2001).

Figura 3. Valores de humedad volumétrica calculados para capacidad de campo (CC) y punto de marchitez permanente (PMP) (A), y valores calculados de agua disponible (B), graficados frente a los valores medidos en los horizontes muestreados de doce pedones evaluados en el presente estudio. Las líneas rojas indican los modelos de regresión lineal ajustados. Los valores calculados de CC y PMP fueron estimados mediante la ecuación de van Genuchten (van Genuchten, 1980), utilizando los parámetros de ajuste obtenidos a través de Rosetta1 (Schaap *et al.* 2001).

The atmospheric water balance estimated for pedon P6 (lowlands of San Carlos) showed water deficit in just three months (February - April), with high precipitation values except for September and January, where there is a significant decrease in precipitation values. The landscape's magnitude and rainfall distribution made it possible for ten months with high values of soil available water (May - February), further depleting TSAW completely from March to April (**Figure 4 F**).

For pedon P7 (Talamanca Piedmont oriented to Buenos Aires), the atmospheric water balance was negative for four months only (December - March). This period of decay in rainfall significantly reduced available water during the first four months, depleting completely TSAW for two months (February and March) but with available water for the rest of the ten months (**Figure 5 A**).

Curiously, when assessing the Mountains of Acosta landscape, the atmospheric water balance was similar to that found for landscape in Hojancha (**Figure 4 A and B**) with a precise period (July - August) where the rainfall amount decreased considerably. Due to this behavior, pedon P8 showed available water for seven months (May - November) and a five-month period (December - April) during which time TSAW was depleted entirely (**Figure 5 B**).

High precipitation rates characterize the southeastern region of Costa Rica. There is the landscape Mountains of Peninsula de Osa, where the atmospheric water balance showed a rainfall decrease from January to March and maximum precipitation values from September to October. The two pedons studied within this landscape (P9 and P10) presented differences in the TSAW. Pedon P9 was depleted entirely during March (one month), while this depletion extended for February and March in pedon P10 (**Figure 5 C** and **D**).

On the other hand, the Caribbean region of Costa Rica presents weather conditions with high rainfall events distributed during the year. The atmospheric water balance in the Highlands of Talamanca showed a water surplus for nine months ($DP > Et_0$), with a precise period where the rainfall decreases (March and April), coinciding with a reduction on TSAW for pedon P12 during those months mentioned above (**Figure 5 E**). Nevertheless, this pedon did not show a deficit in available water (where soil gets totally dry) throughout the year.

Similar behavior was found in the Mountains of Tortuguero (pedon P13), where the surplus period extended for ten months with a reduction in rainfall during March-April. *DP* values were higher for this landscape than those values found in the Highlands of Talamanca. Indeed, a similar behavior to pedon 12 was found for pedon 13, where there was a decay in TSAW for March and April, without a clear soil water deficit (**Figure 5 F**).

4.3. Soil moisture regime, water availability and production potential

While evaluating the behavior of available water in the control section (AWCS) for the twelve pedons assessed in the present study (**Table 3**), we found agreement with TSAW trends described above in the soil water balance after infiltration (**Figures 2** and **3**). From these results, pedons were grouped into three categories following the guidelines described in **Table 2**:

1) Pedons with water deficit (virtual depletion of available water) in the control section for 90 or more cumulative days during the year were classified within the Ustic soil moisture regime (Ustic SMR).

2) Pedons with a water deficit in the control section for less than 90 cumulative days were classified within the Udic soil moisture regime (Udic SMR).

3) Pedons with no water deficit in the soil control section throughout the year were classified within the Perudic soil moisture regime (Perudic SMR).

The first group included pedons studied in landscapes Mountain of Hojancha (P1 and P2), Talamanca piedmont oriented to Valle del General (P3, P4 and P5), and Mountains of Acosta (P8) (**Table 3**). Pedons P1 and P2 presented a water deficit on AWCS for almost six consecutive months (212 cumulative days). Soil water deficit in the control section for pedon P3 extended for 120 cumulative days (four consecutive months), while for pedons P4 and P5 extended for 151 cumulative days (five months).

Similarly, pedon P8 presented a total of 151 cumulative days (five consecutive months) with water deficit. All these aforementioned results allowed us to classify these six pedons under the Ustic SMR, with a period of time of 90 consecutive days or more with water deficit in the control section (**Figures 4 A-E** and **5B**).

The second group included pedons from the landscapes Lowlands of San Carlos (pedon P6), Talamanca piedmont oriented to Buenos Aires (pedon 7), and Mountains of Península de Osa (pedons P9 and P10). Pedons P6 and P7 presented AWCS totally depleted for two consecutive months (61 and 59 consecutive days respectively). Pedons P9 and P10 presented an AWCS deficit for 31 and 59 consecutive days. Therefore, Udic SMR was assigned to these four pedons (less than 90 or consecutive days with AWCS hydric deficit) (**Table 3**).

Finally, soil sampled and described in the landscapes Highlands of Talamanca Valley (pedon P12) and Mountains of Tortuguero (pedon P13) were included in the third group (**Table 3**). Both pedons presented AWSC surplus throughout the whole year (no deficit period for 365 days). Therefore, both pedons were classified within the Perudic SMR (no AWCS total depletion along the year), in agreement with the conditions described on their corresponding soil water balance, where soil holds available water for twelve months, with a reduction in total available water during moths where $DP < ET_o$ but without depleting it totally (**Figure 5 E** and **F**).
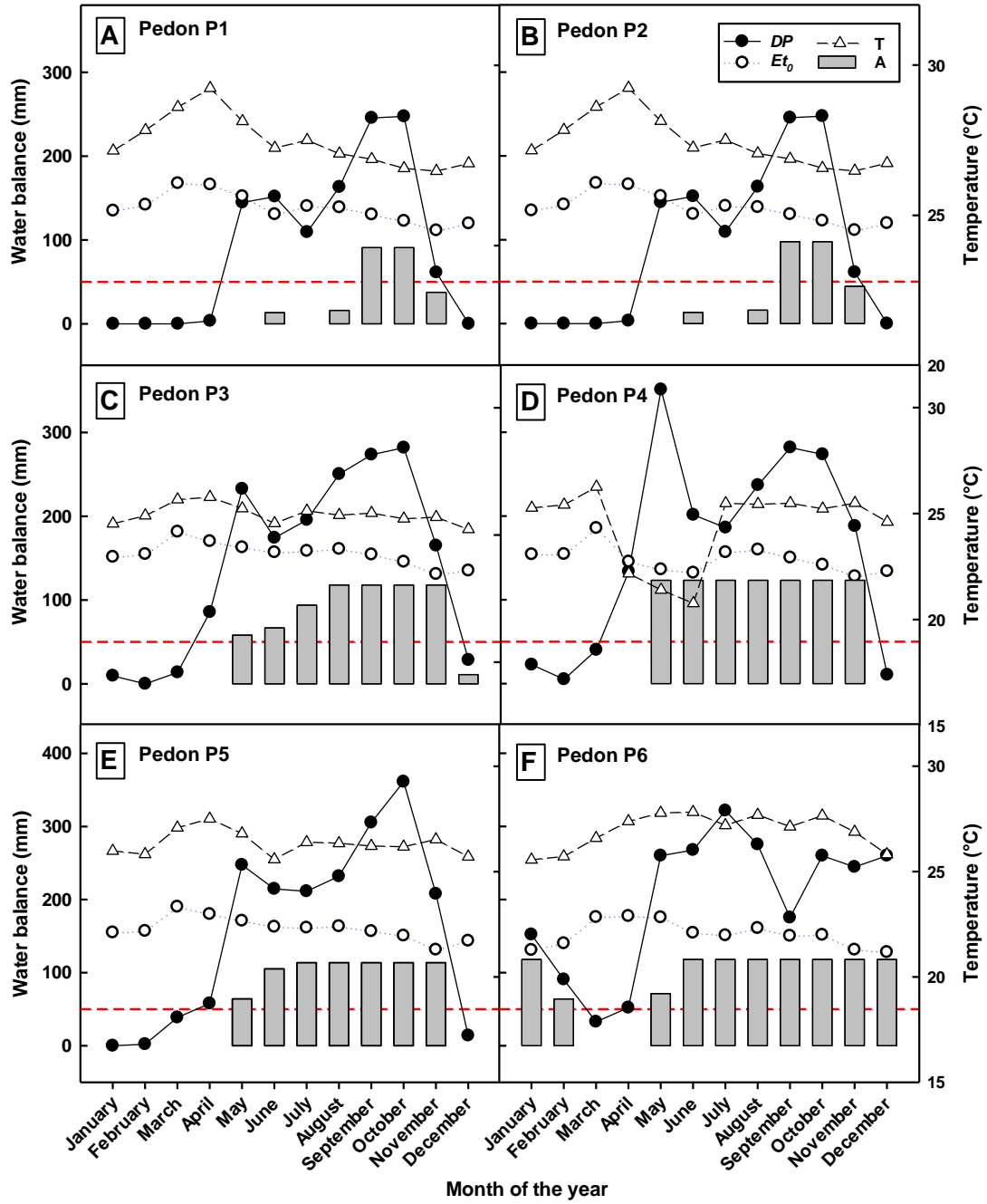
Figure 4. Soil water balance after infiltration calculated for soil pedons: Altos del Socorro (A), San Isidro, Monterromo (B), La Ceniza (C), El Porvenir (D), El Guayacán (E), and Crucitas de Cutris (F). 2016. DP: dependable precipitation (mm), *ET~o~*: potential evapotranspiration (mm), T: temperature (°C), A: soil total available water (mm). Red slashed lines represent 50 mm of available water in the moisture control section (AWCS) as established by Soil Survey Staff (1999).

Figura 4. Balance hídrico del suelo posterior a la infiltración calculado para los pedones: Altos del Socorro (A), San Isidro, Monterromo (B), La Ceniza (C), El Porvenir (D), El Guayacán (E) y Crucitas de Cutris (F). 2016. DP: precipitación confiable (mm), *ET~o~*: evapotranspiración potencial (mm), T: temperatura (°C), A: agua total disponible en el suelo (mm). Las líneas rojas discontinuas representan 50 mm de agua disponible en la sección de control de humedad (AWCS), según lo establecido por el Soil Survey Staff (1999).
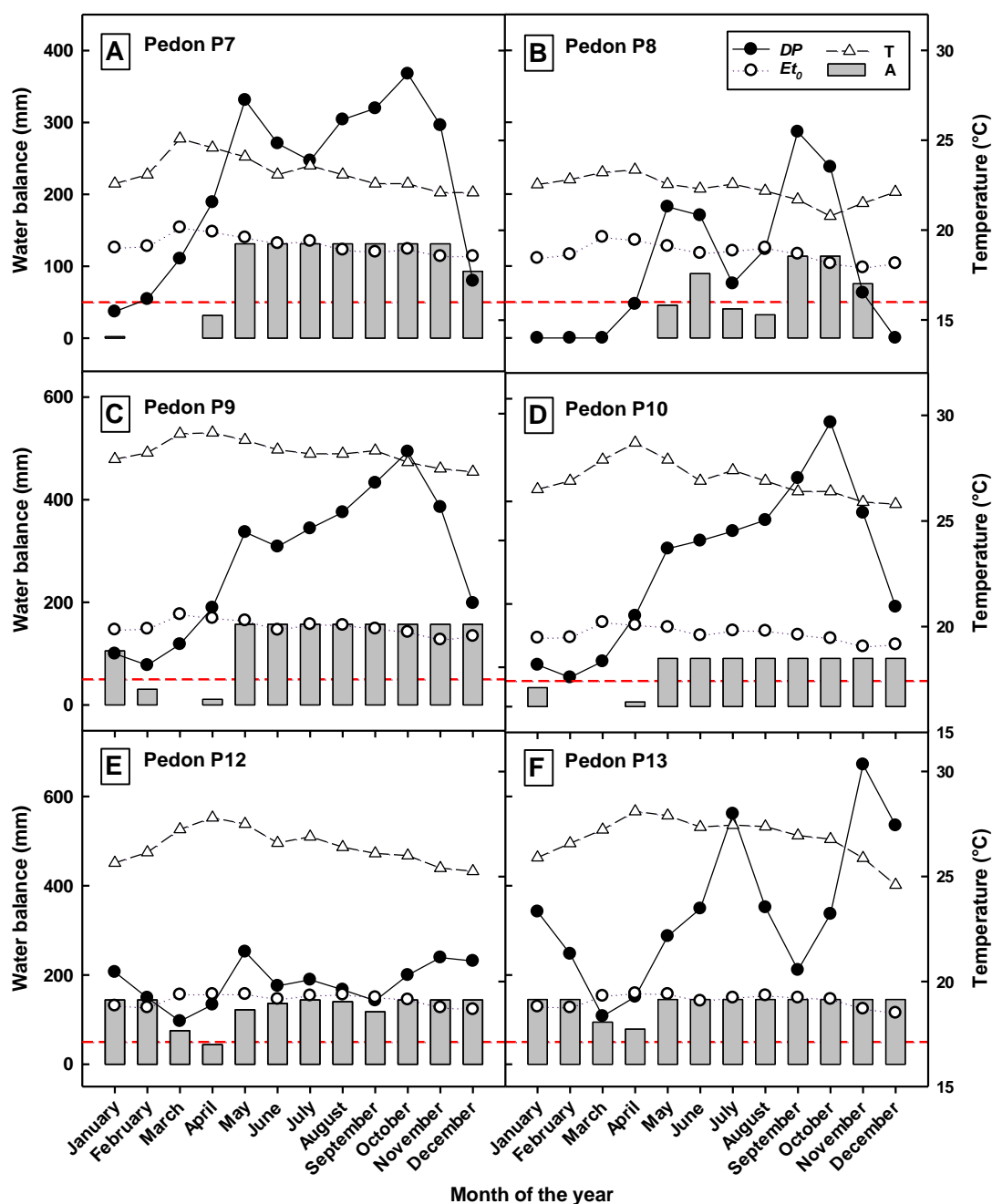
Figure 5. Soil water balance after infiltration calculated for six pedons: Biolley (A), Colorado de Acosta (B), Estación La Gamba (C), Rincón de Osa (D), Los Ángeles, Talamanca (E) and Cerro Coronel (F). DP: dependable precipitation (mm), ET_o: potential evapotranspiration (mm), T: temperature (°C), A: soil total available water (mm). Red slashed lines represent 50 mm of available water in the moisture control section (AWCS) as established by Soil Survey Staff (1999).

Figura 5. Balance hídrico del suelo posterior a la infiltración calculado para los pedones: Biolley (A), Colorado de Acosta (B), Estación La Gamba (C), Rincón de Osa (D), Los Ángeles, Talamanca (E), y Cerro Coronel (F). 2016. DP: precipitación confiable (mm), ET_o: evapotranspiración potencial (mm), T: temperatura (°C), A: agua total disponible en el suelo (mm). Las líneas rojas discontinuas representan 50 mm de agua disponible en la sección de control de humedad (AWCS), según lo establecido por el Soil Survey Staff (1999).

The SMR selected for all pedons assessed in the present study allowed us to designate the taxonomic Suborder for nine pedons (**Table 4**), while the SMR determined the taxonomic Subgroup for pedon P8 (*Ustic Palehumults*). Curiously, taxonomic subgroup designed for pedons P9 and P12 did not include an implicit SMR, in this case *Andic Palehumults* and *Typic Palehumults,* respectively.

5. Discussion

5.1. Pedotransfer functions performance and soil available water

The low values of soil available water (both TSAW and AWCS) observed in the pedons assessed (**Figure 2**) could be explained by the dominance of kaolinite, gibbsite, goethite, and hematite in their clay mineralogy (Camacho *et al.* 2021), which is characteristic of highly weathered soils like Ultisols and Oxisols (West *et al.* 1997, Buol and Eswaran 1999). All these minerals provide soil characteristics like strong grades of structure development, low capacity of water retention and good drainage (Lal 1979, West *et al.* 1997, Buol and Eswaran 1999). This Oxidic-Kaolinitic mineralogy has been reported for other Alfisols, Ultisols and Oxisols in Costa Rica (Alvarado *et al.* 2014, Pincus *et al.* 2017, Camacho *et al.* 2021). Differences in clay minerals could affect the magnitude of wetting-drying phenomena during periods of high precipitation (surplus) and periods where ET_o exceeds precipitation (deficit), as reported by Jackson (1973) and Forsythe (1976). Indeed, soil clay mineralogy strongly affects soil water retention capacity. For instance, when assessing the fit parameters of van Genuchten's equation (the main model used to estimate and describe SWRC), they change dramatically due to variations in clay minerals, like the parameter α (air entry suction) is higher for kaolinitic than for montmorillonitic clay mineralogy samples, which leads to the underestimation of θ values through pedotransfer functions (Hodnett and Tomasella 2002).

Therefore, in absence of measured values for FC and PWP, pedotransfer functions (PTF's) like those available in Rosetta1® software should be used carefully, especially in soils with clay mineralogy like those assessed in present study. In this regard, PTF's developed and calibrated for soils from the humid tropics are quite scarce, and further research should be conducted to validate this approach (Hodnett and Tomasella 2002, Tomasella *et al.* 2000).

Table 3. Available water in control section (AWCS) along the months of the year and soil moisture regime assigned to twelve pedons studied in seven regions of Costa Rica.

Tabla 3. Agua disponible en la sección de control de humedad (AWCS) a lo largo de los meses del año y régimen de humedad del suelo asignado a doce pedones estudiados en siete regiones de Costa Rica.

Pedon	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Ustic soil moisture regime												
P1 Altos del Socorro												
AWCS (mm)	**0.00***	**0.00**	**0.00**	**0.00**	**0.00**	13.41	**0.00**	16.15	19.75	19.75	19.75	**0.00**
P2 San Isidro de Monteromo												
AWCS (mm)	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	13.41	**0.00**	16.15	19.64	19.64	19.64	**0.00**
P3 La Ceniza												
AWCS (mm)	**0.00**	**0.00**	**0.00**	**0.00**	13.33	13.33	13.33	13.33	13.33	13.33	13.33	11.10
P4 El Porvenir												
AWCS (mm)	**0.00**	**0.00**	**0.00**	**0.00**	15.31	15.31	15.31	15.31	15.31	15.31	15.31	**0.00**
P5 El Guayacán												
AWCS (mm)	**0.00**	**0.00**	**0.00**	**0.00**	16.38	16.38	16.38	16.38	16.38	16.38	16.38	**0.00**
P8 Colorado de Acosta												
AWCS (mm)	**0.00**	**0.00**	**0.00**	**0.00**	16.38	16.38	16.38	16.38	16.38	16.38	16.38	**0.00**
Udic soil moisture regime												
P6 Crucitas de Cutris												
AWCS (mm)	13.92	13.92	**0.00**	**0.00**	13.92	13.92	13.92	13.92	13.92	13.92	13.92	13.92
P7 Biolley												
AWCS (mm)	2.16	**0.00**	**0.00**	16.38	16.38	16.38	16.38	16.38	16.38	16.38	16.38	16.38
P9 La Gamba												
AWCS (mm)	12.79	12.79	**0.00**	10.89	12.79	12.79	12.79	12.79	12.79	12.79	12.79	12.79
P10 Rincón de Osa												
AWCS (mm)	12.22	**0.00**	**0.00**	9.08	12.22	12.22	12.22	12.22	12.22	12.22	12.22	12.22
Perudic soil moisture regime												
P12 Los Ángeles												
AWCS (mm)	15.55	15.55	15.55	15.55	15.55	15.55	15.55	15.55	15.55	15.55	15.55	15.55
P13 Cerro Coronel												
AWCS (mm)	12.08	12.08	12.08	12.08	12.08	12.08	12.08	12.08	12.08	12.08	12.08	12.08

*Bold AWCS value: months with total depletion of available soil water in the control section.

Table 4. Taxonomic classification and selected features for twelve pedons sampled and described in seven sectors of Costa Rica.

Tabla 4. Clasificación taxonómica y características seleccionadas de doce pedones muestreados y descritos en siete sectores de Costa Rica.

Pedon's name Taxonomic Subgroup	Soil depth	TSAW [*]	Drainage class[†]	Soil moisture regime	Vegetation or Crop (Species)
	cm				
P1 Altos del Socorro					
Kandiustalfic Eutrustox	190.0	9.09	Well drained	Ustic	Coffee
					(*Coffea arabiga*)
P2 San Isidro, Monteromo					
Typic Rhodustalfs	190.0	9.78	Well drained	Ustic	Coffee
					(*Coffea arabiga*)
P3 La Ceniza					
Plinthic Kandiustox	200.0	11.79	Well drained	Ustic	Sugarcane
					(*Saccharum officinarum*)
P4 El Porvenir					
Anionic Acrustox	200.0	12.33	Well drained	Ustic	Sugarcane
					(*Saccharum officinarum*)
P5 El Guayacán					
Anionic Acrustox	200.0	11.37	Well drained	Ustic	Sugarcane
					(*Saccharum officinarum*)
P8 Colorado de Acosta					
Ustic Palehumults	180.0	14.55	Well drained	Ustic	Forest
					Various species
P6 Crucitas de Cutris					
Plinthic Kandiudox	170.0	11.80	Moderate drained	Udic	Grassland
					(*Bracharya* spp.)
P7 Biolley					
Typic Kandiudox	180.0	13.13	Well drained	Udic	Coffee
					(*Coffea arabiga*)
P9 La Gamba					
Andic Palehumults	200.0	15.73	Well drained	Udic	Forest
					Various species
P10 Rincón de Osa					
Rhodic Kandiudox	200.0	9.39	Well drained	Udic	Forestry
					(*Vochysia guatemalensis*)
P12 Los Ángeles					
Typic Palehumults	200.0	14.40	Well drained	Perudic	Forest
					Various species
P13 Cerro Coronel					
Andic Haploperox	200.0	14.51	Well drained	Perudic	Forest
					Various species

*TSAW: Total soil available water calculated throughout equation 5.

† Drainage classification assigned following Schoeneberger *et al.* (2002).

5.2. The soil water balance after the infiltration approach

Despite the availability in the literature of several models to compute the soil water balance and further soil moisture regime (SMR) such as EPIC, Billaux, or the classical Newhall (Newhall 1972, Costantini *et al.* 2002, Winzeler *et al.* 2013), most of them were developed, calibrated and validated in the temperate regions, covering some assumptions that could be impractical for tropical climate conditions like those present in Costa Rica (Rojas-Morales 2012). Indeed, some authors have reported discrepancies in the SMRs obtained with these models, for instance, the overestimation of Xeric regimes by the Billaux model, or the overestimation of Ustic regimes by the Newhall model (Constantini *et al.* 2002).

In this regard, the soil water balance approach developed in the present research included both climatic and edaphic variables, which are more adequate to describe the soil water dynamics and its implications into the SMR assignment under tropical conditions. For instance, the ET_o is calculated with the model proposed by Hargreaves and Samani (1985), which requires minimal data, as well as the use of *DP* (a probabilistic rainfall value) and the soil water retention in the control section. This simple method provides a simpler framework to determine the SMRs when comparing with the aforementioned models, which tend to be cumbersome to use, or require more data that limit its use (Constantini *et al.* 2002, Bonfante *et al.* 2011, Wang *et al.* 2015).

According with Soil Survey Staff (1999) the SMR should be estimated considering monthly mean precipitation inferred from "data series from normal years" or a year plus minus one standard deviation of the long-term mean annual precipitation ($\mu \pm \sigma$). However, the use of "normal years" has been challenged by other authors, because reduces the amount of useful data for respective calculus, where one standard deviation becomes very restrictive (Costantini *et al.* 2002, Emadi *et al.* 2015).

In present study, *DP* allows a 75% probability of occurrence (probable rainfall in 3 of 4 years), resulting more suitable for studies under tropical climatic conditions, in agreement with those established by Hargreaves and Vogler (1985) and previous studies about rainfall, climate and agricultural potential in Costa Rica (Radulovich 1987, Carmona and Radulovich 1988).

Additionally, trends in the atmospheric variables assessed in present study were comparable to those described by Solano and Villalobos (2001) for corresponding climatic subregions, as well seasonal behavior on rainfall regime in Costa Rica (Rojas-Morales 2012).

Interestingly, midsummer droughts (MSD; called "veranillos" in Central America) were clearly observed during the middle of the year for two landscapes (Mountains of Acosta and Hojancha). The genesis of these MSD's obeys to the influence of the several climatic phenomena, including fluctuations in the Eastern Pacific intertropical convergence zone (ITCZ), El Niño South Oscillation (ENSO) and the Intra Americas low-level jet (IALLJ), providing climatic conditions that reduce the rainfall amounts and distribution during July and August within Central America (Magaña *et al.* 1999, Amador 2008, Amador *et al.* 2006).

This trend in the atmospheric water balance (an MSD) has been previously reported and discussed for Central and North Pacific regions (Radulovich 1987, Carmona and Radulovich 1988, Radulovich 1990, Magaña *et al.* 1999), in agreement with our results observed (**Figures 4** and **5**).

5.3. Soil moisture regime, water availability and production potential

Despite results reported by van Wambeke (1987) in Costa Rica, where Udic SMR was assigned to the regions Valle del General and Acosta (pedons 3, 4, 5 and 8), the soil water balance after infiltration calculated for these pedons indicates that Ustic SMR is more suitable under these pedoclimatic conditions. Consistently, rainfall decreased during the middle of the year (Jun-Aug) in both landscapes (**Figure 4** and **5**), in agreement with the MSD's reported for the Central-South Pacific region (Carmona and Radulovich 1988, Solano and Villalobos 2001, Rojas-Morales 2012).

Interestingly, this Ustic SMR assigned to the aforementioned pedons could explain the extensive distribution and elevated yields of coffee (*Coffea arabiga* L.) in the region of Acosta, as well the extensive crop of sugarcane (*Saccharum officinarum* L.) in Pérez Zeledón and Buenos Aires, due to the need of a water deficit period in the physiology of both crops to carry out certain processes such as: 1) quiescent growth period and the development of the inflorescence in coffee (DaMatta and Ramalho 2006) and 2) dry matter partition in the plant and further sucrose concentration increase in the stem before the sugarcane harvest (Inman-Bamber and Smith 2005).

The differences between the SMR obtained in present study and their corresponding values reported in literature (**Figure 6**) could be explained by differences in the calculation procedures, climatic parameters, and certain assumptions of Newhall model (van Wambeke 1987). For instance, this model assumes 50 mm of water available within control section, which is considerable higher than the values found in this study (**Table 3**).

In addition, the Newhall model handles monthly precipitation (PM) under two main conditions: 1) heavy rainfall (HP) events that immediately enters the soil (where HP = PM/2) and 2) light rainfall (LP) which could not infiltrate within the soil profile due to lost by evapotranspiration (Newhall 1972).

Soil infiltration process is described by Horton (1940) as a sequence of events where during a rainfall or irrigation event water enters the soil profile. When rainfall intensity exceeds infiltration capacity and fills surface depressions, water in excess moves as runoff, constituting a fundamental phenomenon in soil water balance. Evett *et al.* (2012) highlighted the runoff role on water flux change along soil pedon, which conditions the availability of soil water throughout the year.

In Costa Rica, several studies have been performed about runoff rates for Ultisols on coffee plantations (Harmand *et al.* 2007, Villatoro *et al.* 2015) and Andisols (Cannavo *et al.* 2011, Gómez-Delgado *et al.* 2011, Taugourdeau *et al.* 2014) where they reported runoff values corresponding to average monthly rainfall percentage between 3 and 8%. In present study it was selected a value corresponding to 5% of dependable precipitation (*DP*) for each soil water balance performed, due soil morphologic and physical conditions (relief, slope magnitude and soil texture) found for soils assessed were similar to those previously reported (Harmand *et al.* 2007, Villatoro *et al.* 2015).

5.4. Practical implications, caveats, and further research

The soil water balance after the infiltration approach resulted in a powerful tool to assess both the soil water dynamics and SMR assignment, considered satisfactory while determining SMR in highly weathered soils of Costa Rica, and versatile enough to work with limited data when comparing with other hydrologic models available into the literature for the soil moisture regime calculation and assignment (van Wambeke 1987, Costantini *et al.* 2002, Winzeler *et al.* 2013).

Nevertheless, this approach should be used carefully when assessing soils with an actual Aquic soil moisture regime, where the Soil Taxonomy requires evidence of redoximorphic features like mottles and low chroma values (Vepraskas and Sprecher 1997, Soil Survey Staff 1999) to assign this SMR.

In this regard, pedons P12 and P13 were classified within Perudic SMR because they did not present a water deficit period throughout the whole year (**Figure 5**).

However, these same climatic features under poorer drainage would provide conditions for a semi-permanent saturation (waterlogging) and further changes in the soil system's redox status (Vepraskas and Sprecher 1997, Sparks 2003), resulting in morphological features like blue-grayish colors with low chroma values (**Figure 7**).

These features are typical of soils virtually free of dissolved oxygen (and subsequently, with an Aquic SMR), which is difficult to find out without digging the soil profile and describing the morphological soil features (Vepraskas and Sprecher 1997, Schoeneberger *et al.* 2002). Therefore, a sound soil description of these morphological properties (for instance, soil depth, genetic horizons, and their corresponding colors) coupled with the used of this soil water balance approach should be undertaken aiming to properly assign the SMR.
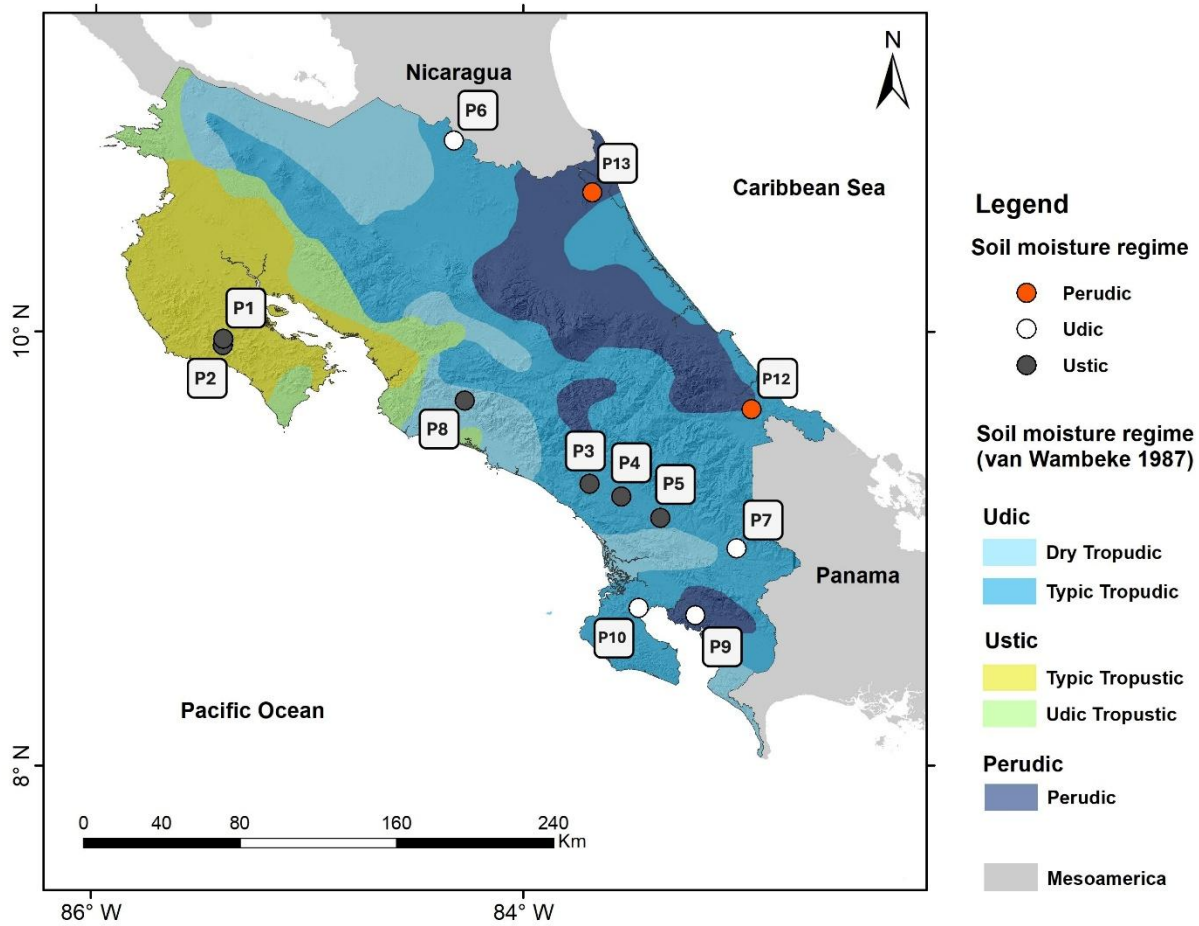
Figure 6. Geographic distribution of soil moisture regime within the Costa Rican territory according with van Wambeke (1987) and SMR determined for 12 pedons in present study (Red, white, and gray dots). Aquic SMR is not shown. SMR classes were consulted from van Wambeke (1987).

Figura 6. Distribución geográfica de los distintos regímenes de humedad del suelo en el territorio costarricense de acuerdo con van Wambeke (1987) y los SMR determinados para 12 pedones evaluados en el presente estudio (puntos rojos, blancos y grises). El régimen de humedad ácuico no se muestra. Las clases de SMR fueron consultadas de van Wambeke (1987).

We encourage further research where this soil water balance approach could be tested in other soil orders like Andisols or Inceptisols, soils with considerable surface extension within the territory of Costa Rica (Mata *et al.* 2020), where other important agricultural activities take place (Camacho-Umaña *et al.* 2024), aiming to extend the use of soil water balance approach and validate its potential results.

Additionally, the use of sensors and other techniques which provide continuous measurements of soil water content (Hidalgo-Campos and Camacho-Umaña 2024) would improve the accuracy of this soil water balance approach while assessing the soil water dynamics and the corresponding identification of months with soil water deficit (Costantini *et al.* 2002).
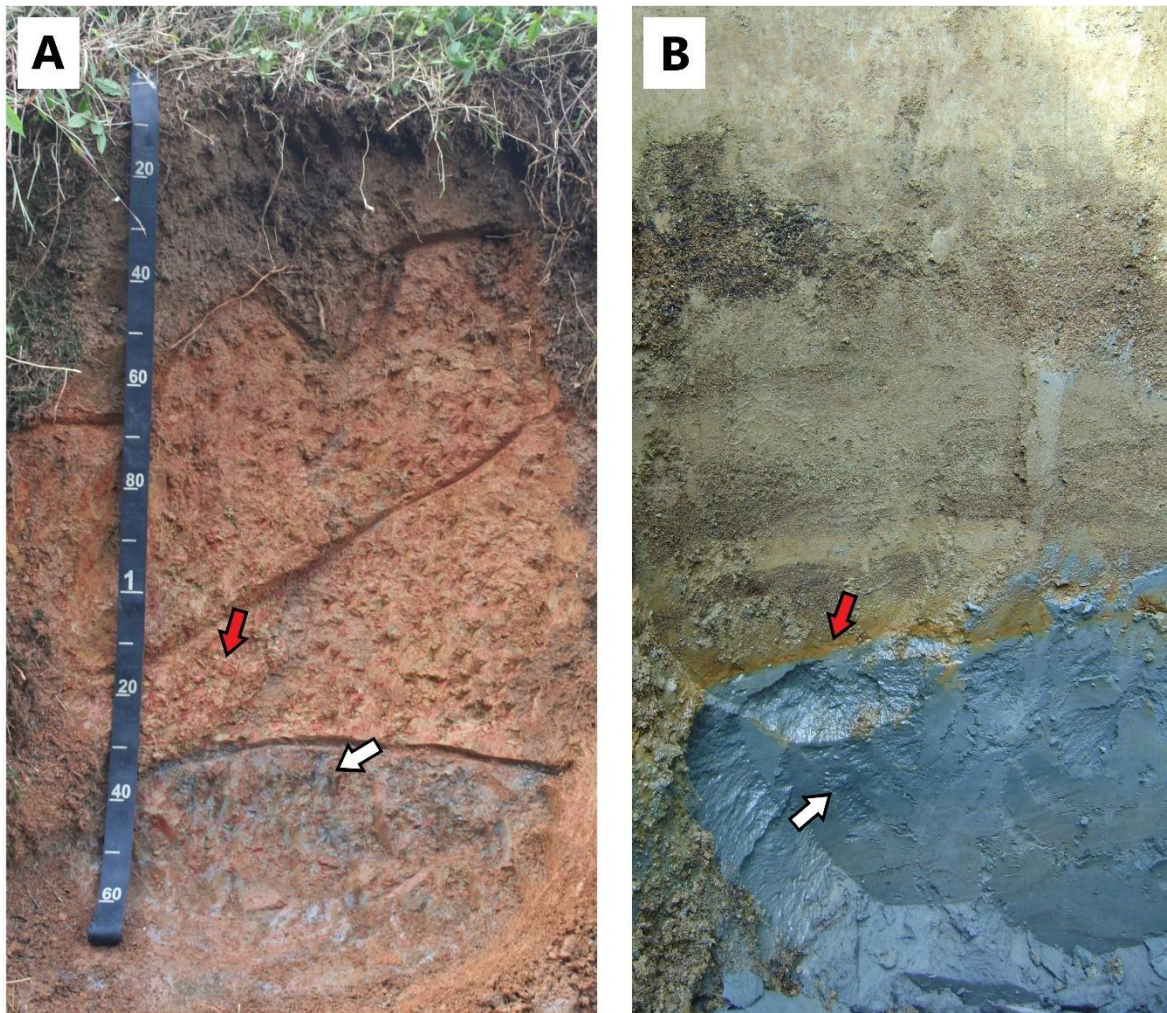
Figure 7. Redoximorphic features assessed in soils from Costa Rica: A) Mottles and blueish colors matrix at the lowlands of San Carlos (Crucitas de Cutris) Province of Alajuela, and B) Iron-reduced matrix in horizon (blue-grayish color) and oxidized boundary (yellowish colors) at the lowlands of Matina (Carradí de Matina), Province of Limón. Red arrows indicate oxidized Fe forms. White arrows indicate reduced Fe forms. Picture 7B is kindly provided by the students of AF4404 "Génesis y clasificación de suelos" course (2014).

Figura 7. Características redoximórficas evaluadas en suelos de Costa Rica: A) Moteados y matriz de colores azulados en las tierras bajas de San Carlos (Crucitas de Cutris), provincia de Alajuela, y B) Matriz con reducción de hierro en el horizonte (color azul grisáceo) y límite oxidado (colores amarillentos) en las tierras bajas de Matina (Carrandí de Matina), provincia de Limón. Las flechas rojas indican formas oxidadas de Fe. Las flechas blancas indican formas reducidas de Fe. La imagen 7B fue amablemente proporcionada por los estudiantes del curso AF4404 "Génesis y clasificación de suelos" (2014).

6. Conclusions

The soil water balance after infiltration approach developed in present study resulted satisfactorily in describing soil moisture dynamics throughout the year, in agreement with climatic patterns reported in the literature. Despite disagreements with SMR previously reported some pedons assessed in present study, our results showed a better agreement with climate conditions and vegetation developing (crops or forestry) within the corresponding regions.

Soils sampled and described in present study presented low soil available water values, explained by their great pedologic development and presence of kaolinite and oxy-hydroxides of Fe and Al as main clay minerals. This condition could explain divergences with soil moisture regime previously estimated through Newhall model, where AWCS assumed is quite higher than that estimated from direct soil water retention measurements.

Further research should be performed to calibrate and validate PTF's in different soil orders from Costa Rica, using the approach developed in the present study for pedons with limited data. We recommend continuing the evaluation of soil water balance approach in other soil orders in Costa Rica under different climatic regions, in order to evaluated performance on SMR determination, as well as soil water balance and soil available water dynamics.

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