

Green water in a brown landscape: Soil characteristics and water availability along an aridity gradient in deciduous oak forests of Michoacán, Mexico

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Abstract

Aim of the study: Green Water at the End of the Dry Season (*GWAEDS*), refers to the soil water that remains available in the root zone of plants at the end of the dry season, and it is an important soil property that may improve accuracy in models of aridity increment derived from climate change scenarios. This work aims to understand key environmental drivers of soil water availability at the end of the dry season, along a gradient of increasing aridity in the soils of temperate deciduous forests of central-western Mexico.

Area of study: The Cuitzeo Basin (19° 30'–20° 05' N; 100° 35'–101° 30' W) within the Trans-Mexican Volcanic Belt in west-central Mexico.

Material and methods: We quantified the *GWAEDS* and correlated it with soil physical and chemical properties, bioclimatic variables, and vegetation greenness (assessed as the Enhanced Vegetation Index, *EVI*) during the dry season across four sites spanning a gradient of increasing aridity in forests with common dominant oak species (*Quercus castanea* Née) on volcanic soils in central-western Mexico.

Main results: We observed differences in *GWAEDS* content across the four sites. Soil properties such as organic carbon content, horizon thickness, and pore space accounted for around 70% of the available soil water. In contrast, bioclimatic variables and vegetation greenness did not correlate significantly with *GWAEDS*. Notably, the site with the lowest annual mean precipitation exhibited the highest *GWAEDS* value, while the site with the second-highest precipitation showed 50% less green water. These findings underscore the buffering capacity of soil properties in regulating water availability.

Research highlights:

- Soil organic carbon, pore space, and horizon thickness explained approximately 70% of the variation in green water content.
- Edaphic properties derived from heterogeneity in pedogenetic processes regulate the green water in an aridity increment scenario.
- Soil properties may buffer water availability, with low-precipitation sites showing higher green water storage.

Keywords: Mexico; pedogenetic processes; precipitation; *Quercus castanea* Née; soil available water; soil organic matter.

Agua verde en un paisaje marrón: Características del suelo y disponibilidad de agua a lo largo de un gradiente de aridez en bosques de encinos caducifolios en Michoacán, México

Resumen

Objetivo del estudio: El Agua Verde al Final de la Estación Seca (*GWAEDS*), por sus siglas en inglés se refiere al agua del suelo que permanece disponible en la zona de las raíces de las plantas al final de la estación seca, y es una propiedad importante del suelo que debe considerarse en los modelos de incremento de aridez derivados de escenarios de cambio climático. Este trabajo tiene como objetivo establecer los reguladores ambientales de la disponibilidad de agua del suelo al final de la estación seca, a lo largo de un gradiente de aridez creciente en bosques templados caducifolios del centro-oeste de México.

Área de estudio: La Cuenca de Cuitzeo (19° 30', 20° 05' N; 100° 35', 101° 30' O) dentro de la Faja Volcánica Transmexicana en el centro-oeste de México.

Materiales y métodos: Cuantificamos el *GWAEDS* y lo correlacionamos con propiedades físicas y químicas del suelo, variables bioclimáticas y verdor de la vegetación durante la estación seca en cuatro sitios a lo largo de un gradiente de aridez creciente en bosques con especies dominantes de encino (*Quercus castanea* Née) en suelos volcánicos en el centro-oeste de México.

Resultados principales: Encontramos que el contenido de *GWAEDS* fue diferente en los cuatro sitios, y que no se correlaciona con variables bioclimáticas, ni con el verdor de la vegetación. Sin embargo, encontramos que el contenido de *GWAEDS* se correlaciona con las propiedades del suelo, como el contenido de carbono orgánico, el espesor de los horizontes y el volumen del espacio poroso, estos parámetros en conjunto, explicaron alrededor del 70% del agua disponible en el suelo. El sitio con la precipitación media anual más baja tuvo el valor de *GWAEDS* más alto, y el segundo sitio con la precipitación más alta mostró 50% menos de agua verde. Esto demuestra el efecto amortiguador que ejerce el suelo sobre la disponibilidad de agua.

Aspectos destacados de la investigación:

- El carbono orgánico del suelo, el espacio poroso y el espesor del horizonte explicaron aproximadamente el 70% de la variabilidad en el contenido de agua verde.
- Las propiedades edáficas resultantes de la heterogeneidad en los procesos pedogenéticos regulan el agua verde en un escenario de incremento de aridez.
- Las propiedades del suelo pueden amortiguar la disponibilidad hídrica, observándose un mayor almacenamiento de agua verde en sitios con baja precipitación.

Palabras clave: agua disponible en el suelo; materia orgánica del suelo; México; precipitación; procesos pedogenéticos; *Quercus castanea* Née.

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Introduction

Climate Change scenarios for central Mexico predict an average reduction of 15% in annual mean precipitation (*MAP*) and an increase of 2 to 4 °C in annual mean temperature (*MAT*). In Michoacán, these projections are even more pronounced, with an expected 24% decrease in *MAP* and an increase in *MAT* of 3.5–5 °C (Rodríguez-Correa et al., 2019). These projected increases exceed the 1.5 °C threshold proposed to prevent ecosystem aridization by 2050 (Park et al., 2018).

Models predicting increased aridity, project a reduction of more than 80% in the area inhabited by certain oak species in Michoacán (Sáenz-Romero et al., 2010; Rodríguez-Correa et al., 2019). However, these models rely on a limited set of factors, such as plant adaptive traits related to water stress or recruitment rates of new individuals. Reliance on specific traits oversimplifies the complexity of ecological systems because these models fail to account for important biotic and

abiotic characteristics. These include plant-soil interactions, species competition, and microclimatic variability which may influence plant development along aridity gradients (Shi et al., 2023). To improve the accuracy of aridity models, it is important to incorporate a broader range of ecological parameters, including plant-soil-climate interactions. This approach could reduce uncertainty in predicting the adaptive phenotypic traits of plants species in response to increasing aridity (Metz & Tielbörger, 2016; Kohl et al., 2018; Berdugo et al., 2022).

One of the primary sources of uncertainty in models studying vegetation responses along geographical gradients is the variability in vegetation cover, soil type, and topographic features (Tschumi et al., 2023; Liang et al., 2024). Many of these studies focus solely on atmospheric conditions, such as the relationship between *MAP*, and *MAT*. This approach assumes that atmospheric conditions are the primary drivers of plant resource availability. However, this approach does not account for other factors, such as soil water availability, often referred to as green water, which influences plant survival and development (Park et al., 2018).

Green water refers to the fraction of rainfall that infiltrates into the soil and becomes available to plants (Falkenmark, 2006). The capacity of soils to store and provide green water is strongly linked to factors such as soil parent material, climate, topography, biota, time, and pedogenetic processes, all of which influence the primary functions of soils (Solleiro-Rebolledo et al., 2015; Kuzyakov & Zamanian 2019). For example, the type and proportion of mineral particles, their spatial distribution, and the concentration of organic matter are important to water storage capacity and availability (Saxton & Rawls, 2006). However, the volume of stored water can be further modified by additional factors, such as evapotranspiration (Campos et al., 2013) and albedo (Barradas and Adem, 1992; Sánchez-Mejía et al., 2014). These factors can reduce the availability of green water, especially at the end of the dry season, where early greenness in deciduous vegetation can exacerbate water loss (Ellsworth and Sternberg, 2015; Manoli et al., 2018).

The soils of the central Mexico, including those across the Trans-Mexican Volcanic Belt, exhibit high heterogeneity due to the complex interplay of topographic, climatic, and eruptive processes, even when derived from similar parent materials (López-López et al., 2023; Solleiro-Rebolledo et al., 2015). This heterogeneity extends beyond soil composition to include differences in soil functions at the basin scale, such as variations in water storage over short geographical distances (Loustau et al., 2001; Biederman et al., 2016; Reichle, 2020).

In seasonal forest ecosystems, the end of the dry season is characterized by a period of reduced physiological activity, during which primary productivity decreases (Ellsworth & Sternberg 2015). Nevertheless, the storage of water, nutrients, and energy during this season are important in supporting the subsequent growing season (Borchert 1994).

This study aims to identify key environmental parameters that influence the Green Water at the End of the Dry Season (*GWAEDS*) across four forest sites along an aridity gradient in the soils of temperate deciduous forests in Michoacán, central-western Mexico. We assessed soil physical and chemical properties, bioclimatic variables, and vegetation greenness. Ultimately, this study provides proxies, such as soil physical parameters, for estimating green water storage capacity at the end of the dry season, as an emergent soil property can improve the accuracy of predictive aridity models under climate change scenarios.

Material and methods

Study area

The Cuitzeo Basin (19° 30'–20° 05' N; 100° 35'–101° 30' W) is an endorheic basin that occupies an area of 4,026 km² and is part of the Lerma-Chapala hydrological region within the Trans-Mexican Volcanic Belt in central-western Mexico (Fig. 1a). The climate within the basin is temperate sub-humid with summer rains and with an increment of aridity from south to north (Fig. 1b). Soils are derived from volcanic materials of intermediate to basic composition in Neogene to Quaternary sequences (Gómez-Vasconcelos et al., 2021; Mendoza et al., 2001). In the southern region of the basin, four sites were selected along a gradient of aridity based on the De Martonne index (see below, Equation 3). From lowest to highest aridity, our sites were *Remolino*, *Atécuaro*, *Umécuaro* and *Jesús del Monte* (Table 1, Fig. 1b). According to the available cartography (Fig. 1c), these sites corresponded to a sequence of Andosols, Luvisols, and Acrisols, which represent a typical pedogenetic sequence in volcanic areas influenced by climatic effects on seasonal systems (Sedov et al., 2003).

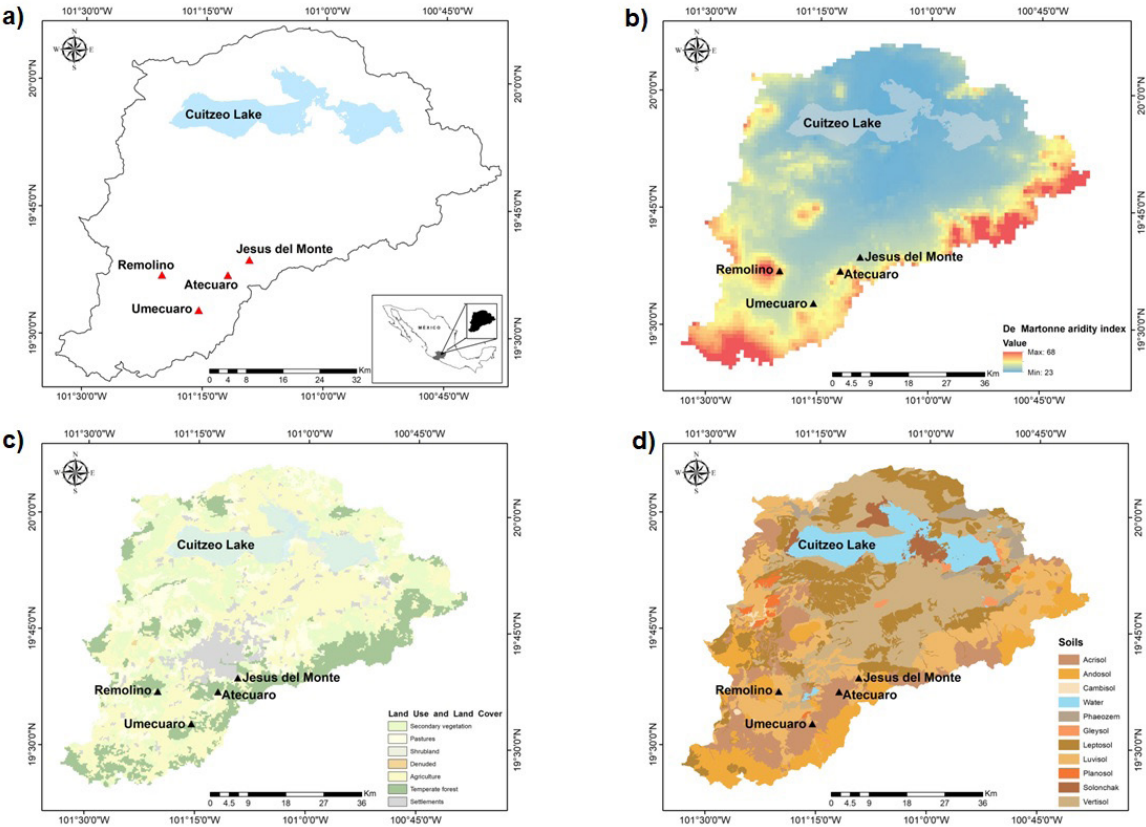


Figure 1. Biophysical aspects of the Cuitzeo Basin, Mexico. a) Study sites indicated by red triangles along an aridity gradient. b) Estimated De Martonne aridity index across the basin. c) Soil groups using the World Reference Base classification system; and d) vegetation cover across the Cuitzeo Basin. Black triangles represent the sampling sites. Prepared using data from the Instituto Nacional de Estadística Geografía e Informática (INEGI, 2022).

Table 1. Sampling site characteristics in the Cuitzeo Basin, Mexico.

Site	<i>Remolino</i>	<i>Atécuario</i>	<i>Umécuario</i>	<i>Jesús del Monte</i>
Lat N	19° 37' 1.6"	19° 37' 5.6"	19° 32' 55.6"	19° 38' 55.6"
Lon W	101° 20' 10.5"	101° 11' 59.2"	101° 15' 33.1"	101° 09' 19.3"
Elevation (masl)	2,556	2,286	2,258	2,138
Annual Mean Precipitation (mm)	1185.3	1023	941	843.5
Annual Mean Temperature (°C)	13.8	15.7	17	17.3
De Martonne Index	49.8	39.8	34.9	30.9

The soils within our study sites do not exhibit any signs of degradation, and the dominant vegetation is deciduous oak forest (Fig. 1d), with *Quercus castanea* Neé as the primary species. *Quercus castanea* Neé, a Mexican oak species in the Lobatae section (red oaks), has a broad geographic and elevational distribution. It is found in the Sierra Madre Occidental, the Central Plateau, the Trans-Mexican Volcanic Belt, and the Sierra Madre del Sur (Valencia, 2004). This species is wind-pollinated, monoecious, and grows as a relatively large tree, 10-18 m in height, but sometimes as a shrub (Trelease, 1924). Among the approximately 13 oak species that occur in this basin, *Q. castanea* is the most abundant and widely distributed, except in the northeastern portion, between 2,000 and 2,800 masl. It can be found in diverse communities including oak forests, pine-oak forests, and subtropical scrublands (Herrera-Arroyo et al., 2013; Aguilar-Romero et al., 2016; Lara-De La Cruz et al., 2020).

Soil sampling and macro-morphological characterization

Soil sampling was conducted during the first week of May 2019, marking the end of the dry season (Chávez-Vergara et al., 2014), with no recorded rainfall in the two weeks preceding the sampling. In each location, an area of 50×50 m was delimited in the most representative zone of the site condition. A pit was then excavated to a depth of 100 cm in the center. The genetic horizons were identified, and their characteristic features were recorded according to FAO guidelines (2009). 2 kg of altered soil samples were taken from each horizon and stored in hermetic plastic bags. Unaltered soil samples were obtained from the horizons using an Uhland-type auger, collecting 100 cm^3 of soil in aluminium foil and stored in hermetic plastic bags. All samples were refrigerated at 4°C until analysis in the laboratory.

Soil physical characterization

The bulk density (ρ_b) was determined using the cylinder method, while particle density (ρ_s) was measured using the pycnometer method. Porosity for each horizon was then calculated based on these densities (Flores-Delgadillo & Alcalá-Martínez, 2010). Soil texture was analyzed using the pipette method (Flores-Delgadillo & Alcalá-Martínez, 2010).

Soil chemical characterization

To quantify total (%) Titanium (Ti) and Zirconium (Zr), samples were ground in a ball mill and passed through a No. 10 sieve. X-ray fluorescence analysis was then performed using a Thermo Scientific Niton XL3t (Solleiro-Rebolledo et al. 2019). Total carbon concentration was determined by drying samples at 105°C until constant weight and pulverizing them in a Restch model MM400 sphere mill. The samples were subjected to dry combustion, CO_2 generated was detected by coulometric analysis using a UIC Model CM150 carbon analyzer (Huffman, 1977; Chávez-Vergara et al., 2018). Since carbonates were absent, organic C was assumed to be equal to total C. pH was evaluated in water (1:10 ratio) and in NaF (1M, 1:50 ratio) using a potentiometer Orion Versa Star Pro, Thermo Scientific, the latter to verify the presence of amorphous minerals (allophanes).

Green Water at the End of the Dry Season (*GWAEDS*)

For each horizon, water content at field humidity (w) was determined by calculating the difference between the wet weight and the dry weight of samples, after drying them in an oven at 105°C for 48 hours. Water content at field capacity (FC) and permanent wilting point (PWP) were determined using a pressure plate apparatus at 33 and 1,500 kPa, respectively. These values were obtained by extracting water from unaltered, capillarity-saturated soil samples. Both FC and PWP were calculated as the difference between the weight of the samples after water extraction and the weight of the samples dried in an oven at 105°C .

The available water content for plants at the end of the dry season in each horizon was then calculated as the difference between w and PWP . Using these values, the bulk density (ρ_b) and the thickness (t_h) of each horizon, the available water content weighted at 1 m^2 per horizon were determined (AWH , Eq. 1).

Finally, we introduce a modification of the soil available water content (AWC) described by Zhang et al. (2019), referred here as the Green Water at the End of the Dry Season (*GWAEDS*, Eq. 2). This modified metric represents the sum of the available water content across the individual soil horizons of a profile, expressed as kg m^3 .

$$\text{Equation 1. } AWH\left(\frac{\text{kg}}{\text{m}^2}\right) = (w - PWP) \times \rho_b \times t_h$$

$$\text{Equation 2. } GWAEDS\left(\frac{\text{kg}}{\text{m}^3}\right) = \sum_1^n AWH_i$$

Environmental Traits and Enhanced Vegetation Index (*EVI*)

We used 19 bioclimatic variables derived from monthly temperature and precipitation data to generate more biologically relevant variables (WorldClim, 2024). These 19 bioclimatic variables were derived from monthly values of precipitation and temperature for the 1970 to 2000 period based on climate data at an arc of 30 s^{-1} from each point selected in the field were extracted using GIS Arc View v3.3 (Lara-De La Cruz et al. 2020). To minimize autocorrelation, the 19 bioclimatic variables were reduced to seven based on a linear correlation threshold of $p < 0.05$. Additionally, we calculated the De Martonne index (Eq. 3), which is used to classify aridity conditions based on the MAP and MAT relationship (Gur et al. 2024) according to:

$$\text{Equation 3. De Martonne index} = \frac{MAP}{MAT+10}$$

We used the Enhanced Vegetation Index (*EVI*) as an indicator to infer the plant-driven extraction of soil water. Monthly scenes from the year 2019, available from the Landsat 8-9 OLI/TIRS Collection 2 Level-1 satellite platform, were used for the path/row (27/46 or 28/46) encompassing the study area. These scenes were selected based on cloud-free conditions and had a spatial resolution of 30 m, projected in the UTM (Universal Transverse Mercator) system, with the WGS84 ellipsoid. The scenes were downloaded from the repository of the U.S. Geological Survey (<https://earthexplorer.usgs.gov/>). Atmospheric correction of each scene was performed using the Semi-Automatic Classification Plugin module implemented in the QGIS 3.26 software. The *EVI* was then calculated using the raster calculator tool in QGIS 3.26.

Statistical analyses

Given the differences in sample sizes (*N*) for edaphic and climatic data, we first conducted a stepwise multiple linear regression analysis between the soil characteristics for individual soil horizons (*N* = 22, corresponding to multiple soil horizons per site). Organic carbon concentration, thickness, and the percentages of clay, sand, and porous space were used as regressors, with *AWH* (as key component of the *GWAEDS*) as the dependent variable, to evaluate the influence of pedogenesis on green water. To assess the relationship between climatic and *EVI* regressors (*N* = 4, corresponding to point data per site), we employed a second approach: a linear regression of *GWAEDS* against selected bioclimatic variables (Bio 1, Bio 2, Bio 3, Bio 4, Bio 7, Bio 14, Bio 18), the De Martonne index, and the increase in *EVI* during the dry season of 2019 (June to November), with *EVI* serving as an indicator of plant water demand. All analyses were performed on Statistica v. 12.0 at an $\alpha = 0.10$ significance level due to the limited number of study sites.

Results

Characteristics of soil profiles at our study sites

Soil profiles at our four study sites exhibit varying degrees of development, reflected in the designation and distribution of the genetic horizons. However, all of them exhibit a noticeable visual and tactile change at a depth of around 30 cm, where a discontinuity is observed, indicating an initial cycle of soil formation. The buried profile has no A horizon beneath the most recent pedogenetic cycle currently exposed at the surface (second cycle) (Fig. 2).

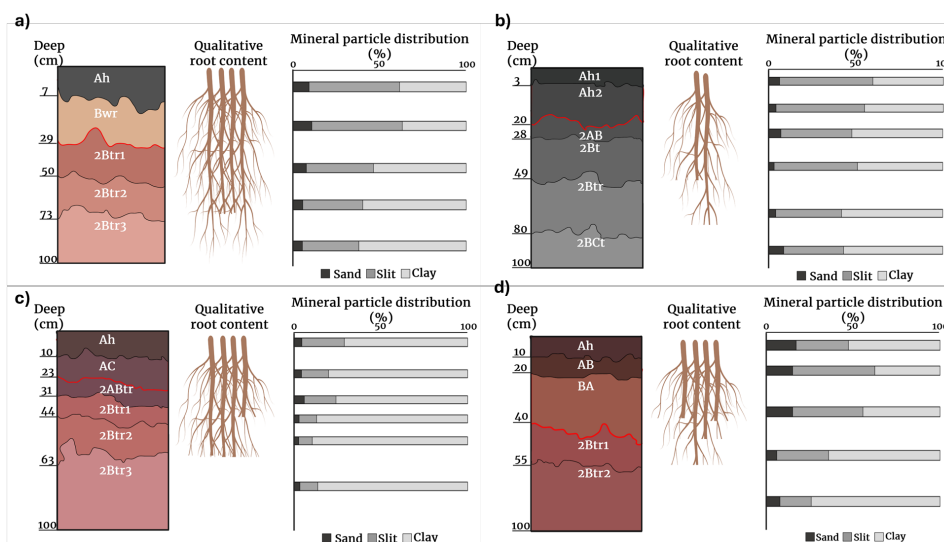


Figure 2. Genetic horizons, root density, and mineral particle distribution in soil profiles. Soil profiles are shown for a) *Remolino*; b) *Atécuaro*; c) *Umécuaro*; and d) *Jesús del Monte*. The red line indicates the lithological discontinuity (noticeable changes in the material from which the soil is formed) in each profile

Remolino profile. The second cycle soil is constituted by Ah (0-7 cm) and Bwr (7-29 cm) horizons, while the first cycle is by 2Btr1 (29-50 cm), 2Btr2 (50-73 cm) and 2Btr3 (73-100 cm) horizons with abundant presence of roots along the entire profile (Fig. 2a). The texture of the upper horizons (second cycle) is silty clay loam, while the buried horizons are clayey. This abrupt

change in texture is strongly influenced by the halving of the silts and the almost doubling of the clays (Fig. 2a). Together with the decreasing pattern of the Ti:Zr ratio (Fig. 3a) and the increase in the particle density values (Fig. 3b) evidence the lithological discontinuity around 30 cm deep. The structure ranges from moderately hard granular in the Ah horizon to tough angular blocks in the inferior horizons; this structure consistency is also reflected in the bulk density values, which are $<0.9 \text{ g cm}^{-3}$ in the topsoil up to 50 cm and greater than 0.9 g cm^{-3} in the lowermost part of the profile (Fig. 3c). Porosity is $>50\%$ of the soil volume throughout the profile (Fig. 3d). The pH in NaF had values >9.4 , except in the 2Btr2 y 2Btr3 horizons (Fig. 3e). The pH in water showed values that decreased as the depth increased from 7.2 to 5.8 (Fig. 3e). The concentration of organic carbon was 84 mg g^{-1} in the Ah horizon with an abrupt decrease of approximately 50% towards the second horizon and values increased from $>5 \text{ mg g}^{-1}$ to 13 mg g^{-1} at the end of the first cycle of soil formation, which perhaps suggests an earlier cycle after 100 cm depth (Fig. 3f).

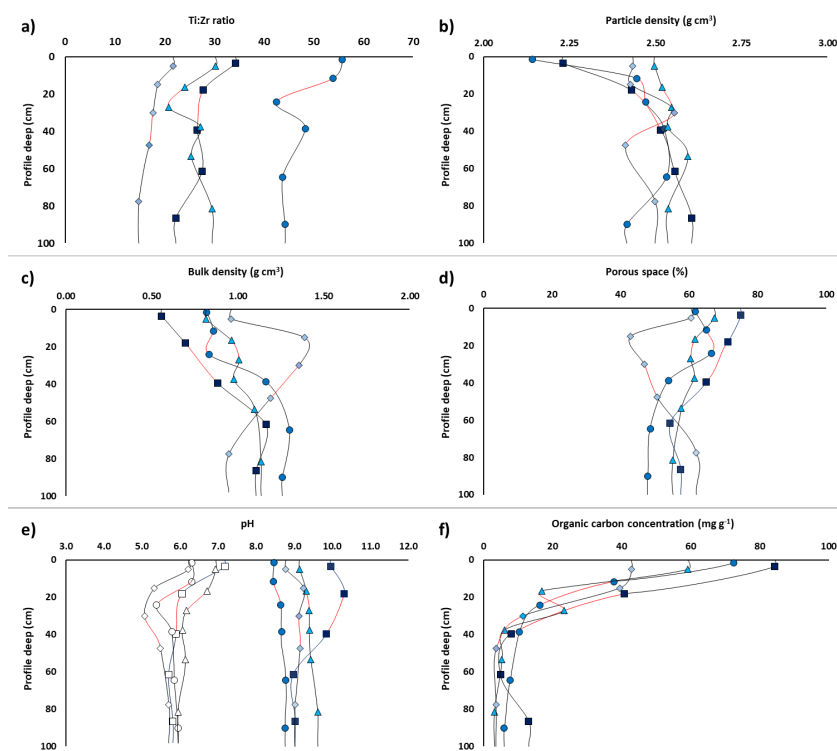


Figure 3. Distribution along soil profiles of a) Titanium:Zirconium ratio; b) particle density; c) bulk density; d) porous space; e) pH (open symbols for measurements in water, filled symbols for measurements in NaF); and f) organic carbon. Red lines indicate lithological discontinuities associated with soil formation. Symbols represent different study sites: squares for *Remolino*, circles for *Atécuario*, triangles for *Umécuaro*, and diamonds for *Jesús del Monte*, Mexico.

Atécuario profile. The soil of the second cycle of soil formation was constituted by Ah1 (0-3 cm) and Ah2 (3-20 cm) horizons, while the first cycle was composed of 2AB (20-28 cm), 2Bt (28-49 cm), 2Btr (49-80 cm), and 2BCt (80-100 cm) horizons. This site had the fewest roots, up to approximately 50 cm deep, and gradually decreased after 70 cm; they were absent (Fig. 2b). The texture of the first four horizons was silty clay, while the texture of the last two horizons was clayey (Fig. 2b). This change in texture, together with the difference in the Ti:Zr ratio (Fig. 3a) and the abrupt increase in particle density (Fig. 3b), gives evidence of a lithological discontinuity around 20 cm depth. Purplish mottles and Mn patches appeared after 49 cm depth, which indicates reducing conditions at some time of the year. The structure went from moderately hard granular to tough subangular blocks. The bulk density is $<0.9 \text{ g cm}^{-3}$ up to 30 cm and greater than 0.9 g cm^{-3} throughout the first formation cycle (Fig. 3c), and the porosity decreased from around 60% of the soil volume to $<50\%$ in the two deepest horizons (Fig. 3d). The pH in NaF had values <9.4 , which evidence the absence of allophanes in this profile (Fig. 3e). The pH in water decreased in the second cycle from 6.3 to 5.4. In contrast, in the first cycle, there was an increase to 6.0 (Fig. 3e). The organic carbon concentration was 72 mg g^{-1} in the Ah1 horizon, with an abrupt decrease of approximately 50% towards the second horizon and a gradual decrease as depth increases (Fig. 3f).

Umécuaro profile. The second cycle in this profile was integrated by Ah (0-10 cm) and AC (10-23 cm) horizons; the first cycle is formed by 2ABtr (23-31 cm), 2Btr1 (31-44 cm), 2Btr2 (44-63 cm) and 2Btr3 (63-100 cm) horizons. There was a very abundant presence of roots up to approximately 45 cm deep, which decreased; after 63 cm, they were absent (Fig. 2c). The texture of all the horizons was classified as clayey, but the clay content increased with depth (Fig. 2c). The Ti:Zr ratio (Fig. 3a) and the variation of the particle density (Fig. 3b) evidenced a lithological discontinuity around 23 cm depth. Purplish mottles and patches of Mn appeared after 23 cm depth, which indicates reducing conditions at some time of the year. The structure went from granular

with moderately hard subangular blocks to slightly hard angular blocks, and the bulk density is $<0.9 \text{ g cm}^{-3}$ only in the first horizon and $>0.9 \text{ g cm}^{-3}$ in the entire rest of the profile (Fig. 3c) with porosity $>50 \%$ of soil volume in the whole profile (Fig. 3d).

The horizons corresponding to the first formation cycle showed pH values in NaF >9.4 (Fig. 3e). The pH in water decreased as the depth increased from 6.9 to 6.0 (Fig. 3e). The organic carbon concentration was 59 mg g^{-1} in the Ah horizon, with an abrupt decrease of more than 50% towards the second horizon and a gradual decrease as depth increases (Fig. 3f).

Jesús del Monte profile. Two formation cycles of this profile were delimited, the second formed by Ah (0-10 cm), AB (10-20 cm), and BA (20-40 cm) horizons and the first cycle by 2Btr1 (40-55 cm) and 2Btr2 (55-100 cm) horizons; there was a high density of roots up to approximately 40 cm deep disappearing entirely after 55 cm (Fig. 2d). The texture ranges from silty clay loam in the topsoil to clayey as the depth increases (Fig. 2d). The Ti:Zr ratio (Fig. 3a) varies very little. At the same time, the variation in particle density is very abrupt in the BA horizon (Fig. 3b), giving evidence of a lithological discontinuity around 40 cm depth. Purplish mottles and Mn patches appeared after 40 cm depth, which indicates reducing conditions at some time of the year. The structure goes from predominantly granular with medium hard subangular blocks to slightly hard subangular blocks. The bulk density is $>0.9 \text{ g cm}^{-3}$ with an abrupt increase from 10 to 40 cm (Fig. 3c), which coincides with the reduction in porosity (Fig. 3d). The horizons have pH values in NaF <9.4 (Fig. 3e). The pH in water showed values that decreased as the depth increased from 6.2 to 5.7 with an abrupt decrease up to 5.0 at 30 cm (Fig. 3e). The organic carbon concentration was 42 mg g^{-1} in the Ah horizon with a gradual decline along the profile (Fig. 3f).

Soil profile water distribution and Green Water Available at the End of the Dry Season (GWAEDS) quantification

Remolino had the highest average value in w and FC (Fig. 4a), while *Jesús del Monte* had the lowest average w (Fig. 4d). Despite this, the distance from w to FC was the smallest compared to the other sites in the second cycle of soil formation, corresponding to the first 40 cm of the profile (Fig. 4d). The *Atécuaro* profile presented the smallest distance between w and PWP , especially after 40 cm, corresponding to the first cycle.

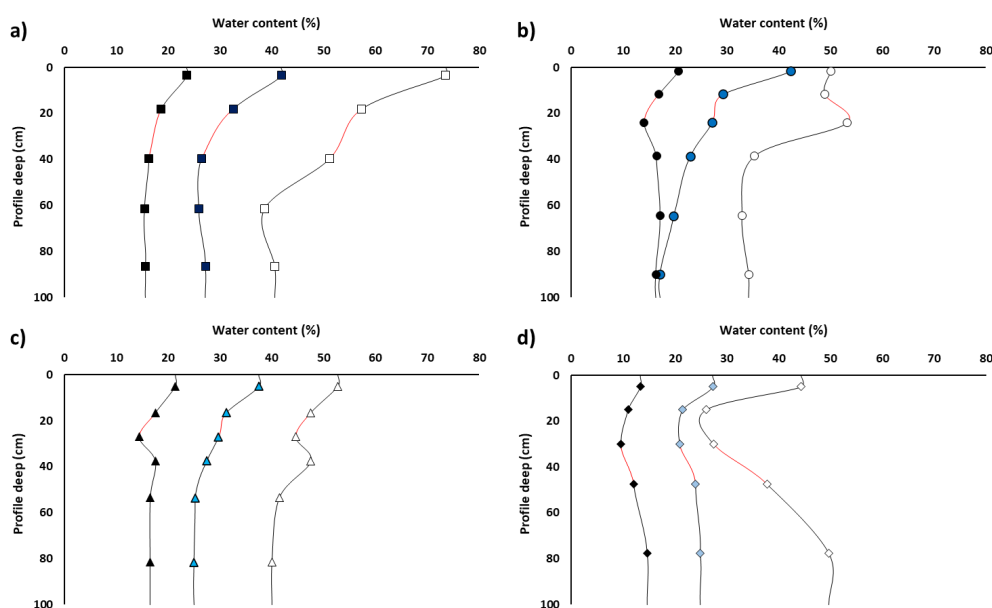


Figure 4. Soil water content at key points along soil profiles. Water content at the permanent wilting point (PWP, black symbols), water content at field humidity at the end of the dry season (w , blue symbols), and field capacity (FC, white symbols) for a) *Remolino*; b) *Atécuaro*; c) *Umécuaro*; and d) *Jesús del Monte*. Red lines indicate lithological discontinuities associated with soil formation cycles.

The water content per horizon (AWH) fluctuated throughout the entire profile for the four soils studied (Fig. 5a). In the surface horizon, the amount of available water was separated into two groups, an approximate value of 6 kg m^{-2} made up of *Remolino* and *Atécuaro*, and another with approximately 13 kg m^{-2} in *Umécuaro* and *Jesús del Monte* (Fig. 5a). From the second horizon, the mass of water fluctuated and was redirected towards a more significant accumulation in *Jesús del Monte*, the site with the lowest rainfall, with 42 kg m^{-2} , *Atécuaro*, the site with the second highest rainfall, had the lowest content of green water in the deepest horizon 1 kg m^{-2} (Fig. 5a). The multiple regression model (Table 2) showed that each horizon's organic carbon concentration, pore space, and thickness significantly explained 66% of the variation in AWH ($n = 22$). The coefficients associated with organic carbon concentration and pore space were positive, while that of thickness was negative.

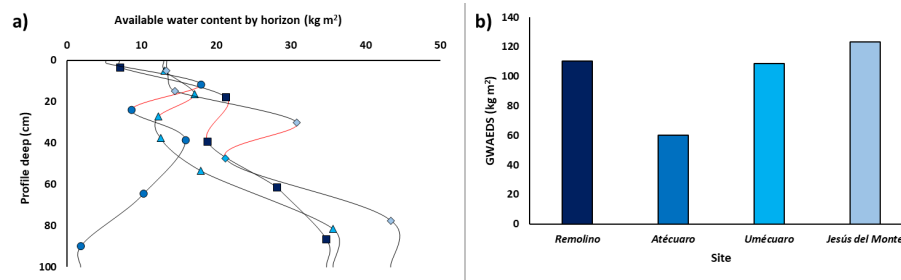


Figure 5. Plant-available water content at the end of the dry season. a) by horizon (as *AWH*); and b) in one cubic meter per site (as *GWAEDS* at 1 m depth). Symbols represent different study sites: squares for *Remolino*, circles for *Atécuaro*, triangles for *Umécuaro*, and diamonds for *Jesús del Monte*.

Table 2. Multiple regression model for Available Water for Horizon (*AWH*) explanation.

Dependent variable	Predictors included	Significant predictors	Coefficients	R^2 (p)
AWH	Organic carbon	Organic carbon	0.79	0.66 (< 0.001)
	Clay			
	Sand	Porous space	1.95	
	Porous space			
	Thickness	Thickness	-1.13	

The *GWAEDS*, as the amount of water accumulated in the entire profile calculated as the sum of each one of the horizons in 1 m² at 1 m depth (kg m⁻³) (Fig. 5b), does not show direct correspondence with *MAP*, the De Martonne index, dry season *EVI* or any of the bioclimatic variables (Table 3). It is even observed that *Jesús del Monte*, the site with the least rainfall, is the one that accumulates the higher content of green water at the end of the dry season, 123 kg m⁻³, and *Atécuaro* (the second highest rainfall), shows 50% less green water content.

GWAEDS in the whole profile showed no significant correlation with the *EVI* and bioclimatic variables analyzed (Table 3). However, when the *GWAEDS* is segmented by the soil formation cycle, it is observed that the same effect of no relationship with the bioclimatic variables is maintained in the first cycle (around >60 cm depth or deep layer). In comparison, in the second cycle of formation (around < 40 cm depth or shallow layer), there is a strong negative correlation with the isothermality (Table 3), which suggests that precipitation does not regulate the green water of the soil.

Table 3. Linear correlation of bioclimatic variables and Green Water at the End of the Dry Season (*GWAEDS*), for whole soil profiles and by the soil formation cycle, in the Cuitzeo Basin, Mexico.

Parameter	GWAEDS		Shallow layer		Deep layer	
	R^2	p	R^2	p	R^2	p
Mean Annual Temperature (Bio 1)	0.217	0.783	0.576	0.424	-0.155	0.845
Mean Diurnal Range (Bio 2)	0.196	0.804	-0.206	0.794	0.427	0.573
Isothermality (Bio 3)	-0.437	0.563	-0.941	0.059	0.139	0.861
Temperature Seasonality (Bio 4)	0.659	0.341	0.693	0.307	0.355	0.645
Temperature Annual Range (Bio 7)	-0.279	0.722	0.078	0.922	-0.439	0.561
Precipitation of Driest Month (Bio 14)	-0.158	0.842	-0.331	0.669	0.044	0.956
Precipitation of Warmest Quarter (Bio 18)	-0.293	0.707	-0.785	0.215	0.214	0.786
De Martonne Index	-0.193	0.807	-0.610	0.390	0.213	0.787
<i>EVI</i> (dry season)	0.374	0.626	-0.235	0.765	0.691	0.309

Discussion

We propose that the Green Water at the End of the Dry Season (*GWAEDS*) indicates the capacity of soils to provide available water for plants in a period of null or negligible rain, representing the minimum amount of water stored in soils. Our study found that soil organic carbon, pore space, and horizon thickness are key factors influencing *GWAEDS*. We did not find any significant relationship between *GWAEDS* and *MAP*, aridity index, vegetation greenness, or any dry season climatic variable evaluated. We found significant differences in *GWAEDS* values among the four study sites. *Jesús del Monte* had the highest *GWAEDS* value (123 kg m^{-3}), despite receiving the lowest rainfall of the four sites (i.e. 850 mm), followed by *Remolino* (110 kg m^{-3}) and *Umécuaro* (108 kg m^{-3}); *Atécuaro* had the lowest value (60 kg m^{-3}) although it had the second highest precipitation value (1,000 mm). This finding suggests that *MAP* may not be directly related to plant water availability at end of the dry season in the studied ecosystems, as water availability is primarily regulated by soil properties and water accessibility by root functional characteristics (Moles et al., 2014; Zhang et al., 2019).

Our findings align with previous research that shows the importance of soils properties in determining soil water storage capacity (Saxton and Rawls, 2006; Dymond et al. 2017; Zhang et al. 2020). Soil organic carbon has been shown to enhance water retention by increasing the capacity of soils to hold water (Rawls et al., 2003; Zhang et al., 2020). This is consistent with our observation of its significant role in regulating *GWAEDS*. Pore space also emerged as a key parameter. Water retention occurs not only on mineral surfaces but also within soil pores (Hao et al., 2008; Kool et al., 2019; Reichert et al., 2020). In contrast, we observed a negative correlation between horizon thickness and available water holding capacity (*AWH*). This aligns with findings that thicker horizons hinder water movement and homogenization within the soil profile (Algayer et al., 2020). These results highlight the dominant role of soil properties over climatic variables in determining *GWAEDS*.

We found clear lithological discontinuities across the soil profiles in the studied sites, which play a crucial role in shaping soil properties and driving the disconnection between *GWAEDS* and climatic conditions. These discontinuities define two distinct soil development cycles, each with differing influences on water storage capacity. Notably, only the most recent phase of soil formation (second cycle) exhibited a positive correlation between *GWAEDS* and isothermality (Table 3). This finding suggests that the relationship between soil water availability and climatic variables such as temperature stability is mediated by the characteristics of the superficial soil layer formed during the second cycle.

Our findings on green water storage at the end of the dry season can explain the wide distribution of the oak species, *Quercus castanea* across the Cuitzeo Basin. The high soil water storage capacity emerges as a main driver supporting this distribution, outweighing other factors such as precipitation, temperature, topography, and soil nutrient availability (Aguilar-Romero et al. 2016). Furthermore, the high phenotypic plasticity observed in traits related to water use in this species enhances its adaptability, for example, by enabling root distribution in areas where groundwater patches form (Cavender-Bares et al., 2004; Lara De la Cruz et al., 2020).

Although precipitation and temperature are critical drivers of primary productivity, the regulatory role of soil in mediating interactions between plant functional attributes and atmospheric conditions should not be overlooked (Wang et al., 2019). This is particularly relevant across broad environmental gradients or in areas with water limitations. For example, Zhang et al. (2019) found a stronger correlation between various leaf attributes and soil water content than with climatic features, even across a De Martonne index range of 34.4 to 10.9. These findings suggest that soil water content is a key regulator of primary productivity under conditions of marked aridity and, during periods of extreme drought (Maysonnave et al, 2022; Zhao et al., 2023).

Conclusions

Our results emphasize the important role of soil properties in controlling water availability at the end of the dry season. Soil organic carbon, pore space, and horizon thickness explained approximately 70% of the variation in green water content, making them key proxies for soil water storage. These properties are among the primary determinants of ecosystem functionality, particularly in arid and semi-arid environments, including seasonal oak forests. This highlights the importance of incorporating soil water content into modelling studies on plant water availability, especially under scenarios of ecosystem aridization and climate change (Moles et al., 2014).

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