Original Research Article

Estimating plant available waterusing pedotransfer function classes to better address water stress in agriculture and forestry in Togo

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ABSTRACT

Plant available water (PAW) also known as total available water (TAW) - the amount of water that the soil can store and return to plants for their physiological needs – is the essential parameter of soil water balance models, which are themselves integrated into crop growth and orientation models (crop type, rotation, estimation of production potential) and in irrigation decision-making tools (irrigation management, water deficit assessment, drainage calculation). Water balance calculation also has multiple applications in forestry: (i) explaining forest dieback phenomena, (ii) defining the suitability of sites for the silviculture of different species by assessing the associated water risk, (iii) defining the canopy density - water resources trade-off for well-considered management of thinning to protect trees from excessive competition for water resources, (iv) developing decision-making tools for forest management.However, soil hydraulic parameters used to calculate the TAW, in particular the water content at field capacity and at permanent wilting point, are often not available from soil maps and their measurement is very time consuming and costly. This study,conducted between April and July 2024, aims to estimate TAW of Togo soils, using pedotransfer function classes (Class PTFs). The performance and reliability of Class PTFs used were first validated by calculating the percentage of applicability, the mean error and the root mean squared residual error by testing 30 soil samples.The TAW estimating was performed on a set of 79 horizons from 50 reference site profiles used to characterise the different types of soil and draw up the soil map of Togo. Spatialization was carried out using QGIS v 2.18.28 software. The results show that over three-quarters of Togo's territory has a TAW above 250 mm, essentially ferrallitic soils (260 to 521.25 mm), hydromorphic tropical ferruginous soils (318.1 mm) and Mull soils (280.55 to 291.9 mm). This study provides a simple diagnostic mapping tool for farmers and forest managers. It introduces a spatial quantification of soil water availability in Togo, which is important for the country's development, as well as for establishing good practices in irrigation and crop management. Moreover, this type of information can support a diverse range of studies and projects aimed at mitigating climate change.

Keywords: Total available water; field capacity; wilting point; water balance calculation.

1. INTRODUCTION

In recent decades, Togo has experienced serious climate disruption [1,2]. Great thermic increases have been registered in the southern and northern plains [3]. Climate change scenarios show that the country is projected to experience unprecedented warming with only a slight increase in precipitation between 2025 and 2100 [4]. Ongoing warming is having a major impact on soil water availability whose assessment constitutes a growing concern.

Soil water mediates important ecosystem services in the critical zone at local, regional, and global scales, including functions related to biomass production of natural and agricultural ecosystems, which are partially regulated by root water uptake [5]. Not all soil water is available to plants, and plant available water (PAW) can be expressed as a fraction of total soil water storage [6, 7]. The PAW fraction, also referred to as total available water (TAW), is commonly defined as the difference between the volume-based water content at field capacity (FC) and at permanent wilting point (WP). Although FC depends on soil layering and a criterion to define negligible flux, the soil water content at some pressure head usually between pF 2.0 (-10 kPa) and pF 2.5 (-33kPa) is often considered as FC [8, 9]. Similarly, although WP may vary according to crop type, plant age and root distribution, it is generally accepted that the soil water content at a pressure head of pF 4.2 (-1600 kPa) is a representative value for WP [10, 11, 12, 13].

The water supply of crops is one of the major variables influencing their productivity and the quality of the products obtained. The TAW- the amount of water that the soil can store and return to plants for their physiological needs - is a major feature of the functioning of the soil-plant-atmosphere system. It is the essential parameter of water balance models, used both in crop growth and orientation models (type of crop, rotation, estimation of potential production) and in irrigation decision-making tools (irrigation management, water deficit assessment, drainage calculation). The output variables of these models can be, for example, a dose of irrigation water, a loss of crop’s yield related to water deficit, a quantity of mineral nitrogen leached, etc. In addition, water resources are one of the determining factors in the adaptation of our forest ecosystems to the predicted climatic upheavals. The assessment of soil water reserves should lead to a better perception of the vulnerability of forest sites to water stress and to more precise management recommendations regarding the choice of species to be planted and forestial techniques [14]. The complexity of the assessment of the water factor, which depends on many parameters (climate, geomorphology, soil, vegetation), leads to the realization of water balances that have multiple specific applications in forestry, in particular the explanation of forest dieback phenomena [15], the definition of the suitability of sites for forestry of different species by an assessment of water risk associated with them [16]. In addition, autecological studies seeking to relate the distribution or growth of different species to their environment generally include the water reserve in the pool of abiotic descriptors used [17, 18]. In particular, "dendroecological" models, which attempt to explain the width of tree rings, which are very sensitive to monthly variations in soil moisture, require a detailed estimate of the water and hydrological balance of the station [19]. The water reserve can also be part of a forestry perspective for the definition of the "canopy density – water resources" trade-off. This balance is necessary for a thoughtful management of thinning to protect trees from too much competition for water resources [20]. On the other hand, in a more pragmatic context of the provision of decision-making tools in forest management, it will be possible to develop a diagnostic tool for forest sites in Togo for use by field foresters. These will be keys to determining the trophic level of soils and water availability of the sites. It is therefore necessary to capitalize on the measured data within shared databases. The results can then be spatialized using a Geographic Information System (GIS) to produce maps of soil available water in Togo.

Soil hydraulic parameters used to calculate the TAW, in particular the FC and the WP,are often not available from soil maps and their measurement is very time consuming and costly. Consequently, pedotransfer functions (PTFs) are typically used to predict hydraulic parameters from already available soil properties such as soil texture information, bulk density and organic carbon content [21; 22]. There are many types of PTFs distinguished in the literature based on their inputs, outputs, underlying algorithms, etc. But the two most basic PTF types, based on the type of data used to derive the PTF, are class and continuous PTFs [23]. A class PTF is essentially an average of some soil property within a group of soils, typically a texture class, while a continuous PTF utilizes detailed particle-size data of each individual particle-size data curve separately, or clay content and bulk density. The most important properties described by a PTF are water retention curves (also called moisture-characteristic curves, relation between pressure head and water content) and hydraulic conductivity curves (relation between hydraulic conductivity and water content). Point estimation PTFs predict water retention at defined water potentials (for example, at field capacity or permanent wilting point to predict available water content).This study aims to quantify the water availability of Togo soils, using class PTF, in direct connection with Togo soil data, to better address water stress in agriculture and forestry in Togo. It provides a simple diagnostic mapping tool for farmers and forest managers.

2. MATERIAL AND METHODS

2.1 Different types of soil in Togo and selection of the reference sites

The Togo soil classification is an application of the French classification [24]. Seven of the ten soil classes in this classification are represented in Togo, but class VIII of sesquioxide soils represents the majority of the soils observed (about three-quarters of Togo's soil). Two major sub-classes represent this class: tropical ferruginous soils covering more than 50 % of Togo's surface area, and ferrallitic soils covering around 20 %. Raw mineral soils or soils that are not very developed, due to erosion or alteration, are mainly represented in the mountains or in the lowlands. The other classes represent only modest but not negligible areas.

The reference site chosen for each type of soil is the one chosen by [25] based on observations on auger soundings, which previously made it possible to approximate the internal variability of the soil unit. It is assumed that this site is the site with the closest soil to the average depth, texture and stoniness values observed in the mapped soil unit.

2.2 Applicability and performance of the pedotransfer function used

At present, no Class PTFs has been identified that are specific to sub-African soils, and those that are used are all of foreign origin. The Class PTFs used in this study is that of [26]. It was selected on the basis of their precision and of available pedological data (Figure 1) [27, 28], the datasets take into account only the type of horizon and its texture, without considering the bulk density of textural classes. However, given that this Class PTFs are established in eco-pedological circumstances that differ from those of sub-Africa, it becomes imperative to evaluate and validate their use. Thus, soil profiles (150 cm deep) were excavated on 10 geo-referenced soil-sampling sites (Figure 2), which belong to the sesquioxide soil class (ferruginous and ferrallitic soils). Basic soil properties were collected, including thickness and bulk density of different soil layers encountered. Texture was estimated from laboratory measurements (percentages clay–silt–sand), according to the triangle of textures of the Aisne (Figure 3). Soil layers were grouped into relatively homogeneous classes distinguished between upper and lowersoil layers. Soil samples were subjected to the same hydric measurements as the soils studied (pF2 and pF4.2). It was initially determined whether the samples in the evaluation data set fall within the ranges of the calibration data sets for the chosen PTF [29], by calculating the applicability percentage (AP). The AP is the percentage of samples examined with texture and structure parameters (bulk density) within the limits of those of the calibration samples. As the AP obtained (88.88 %) was greater than 85 % (Table 1), the chosen PTFs of [26] was maintained for the study. To assess the performance of PTFs, three statistical criteria were applied: mean residual error (ME) and associated prediction standard deviation (PSD), and root mean squared residual error (RMSE). The ME (Equation 1) provides information on the bias of the estimate. The closer ME is to zero, the less biased the prediction. When the mean of ME is positive, the PTFs overestimate $\boldsymbol{\theta}$, whereas if it is negative, they underestimate it. The PSD (Equation 2) is used to estimate the precision of the estimate, which is more precise the closer PSD is to zero. The RMSE (Equation 3) is a measure for the scatter around the 1:1 linear relation between measured and estimated data points. Low values indicate little scatter. Any PTF with an RMSE greater than 0.09 cm3.cm-3 is considered inaccurate and should therefore be rejected [21, 30]. All these statistical criteria calculated (Table 2) validate the use of PTFs of [26].

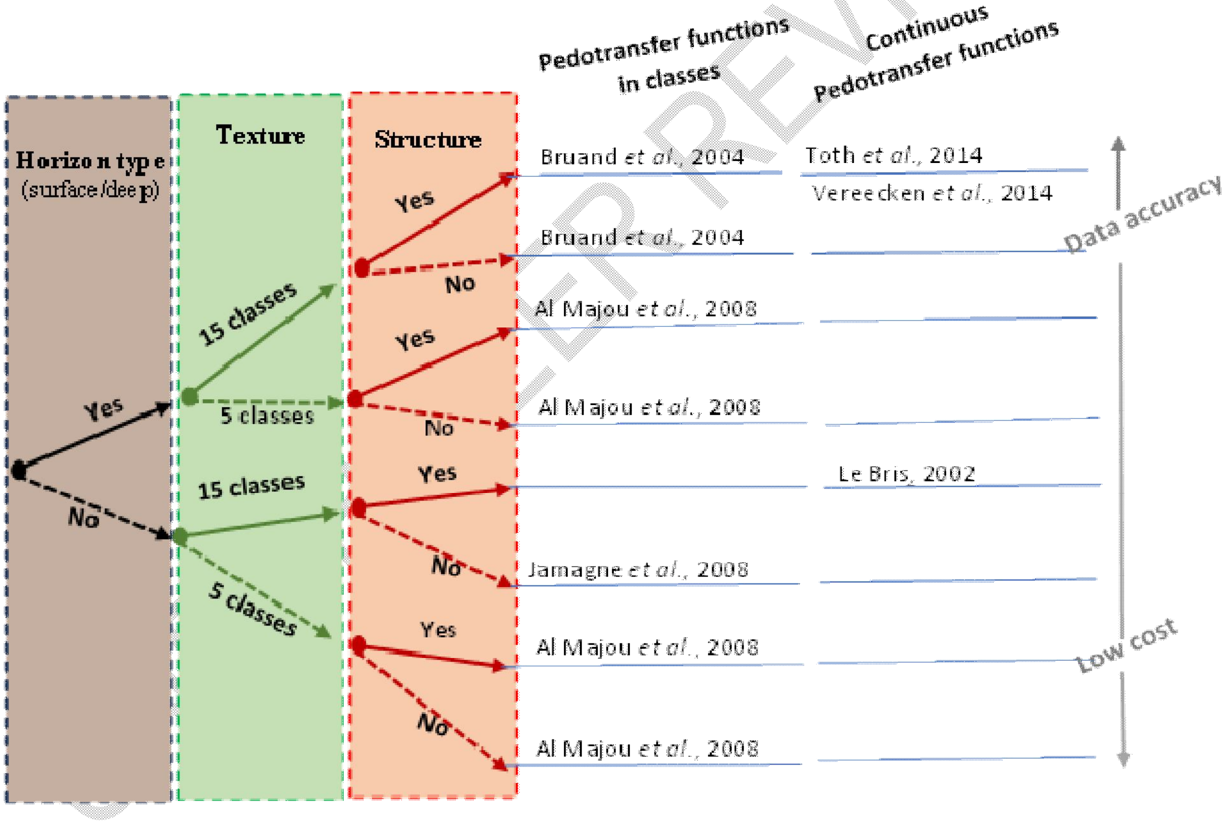

Fig.1.Decision tree for selecting a pedotransfer function based on available data [27]

Table 1.Value of applicability percentage (AP) of the class PTFsof [26]

	Clay (%)	Silt (%)	Sand (%)	Bulk density (g.cm^{-3})	AP (%)
Current study	1-41	-	38-90	0.58-1.63	-
Bruand *et al*. (2004)	1.9-92.9	nd	1.1-90.1	1.1-1.8	88.88

n: number of samples

$$ME = \frac{1}{n}\sum_{i=1}^{n}(\theta_e - \theta_m) \qquad \textbf{(Equation 1)}$$

$$\text{PSD} = \left\{\frac{1}{n}\sum_{i=1}^{n}[(\theta_e - \theta_m) - ME]^2\right\}^{\frac{1}{2}} \qquad \textbf{(Equation 2)}$$

$$\text{RMSE} = \left\{\frac{1}{n}\sum_{i=1}^{n}(\theta_e - \theta_m)^2\right\}^{\frac{1}{2}} \textbf{(Equation 3)}$$

n: number of samples, $\boldsymbol{\theta}$e: estimated soil moisture content ($cm^3.cm^{-3}$), $\boldsymbol{\theta}$m: measured soil moisture content ($cm^3.cm^{-3}$).

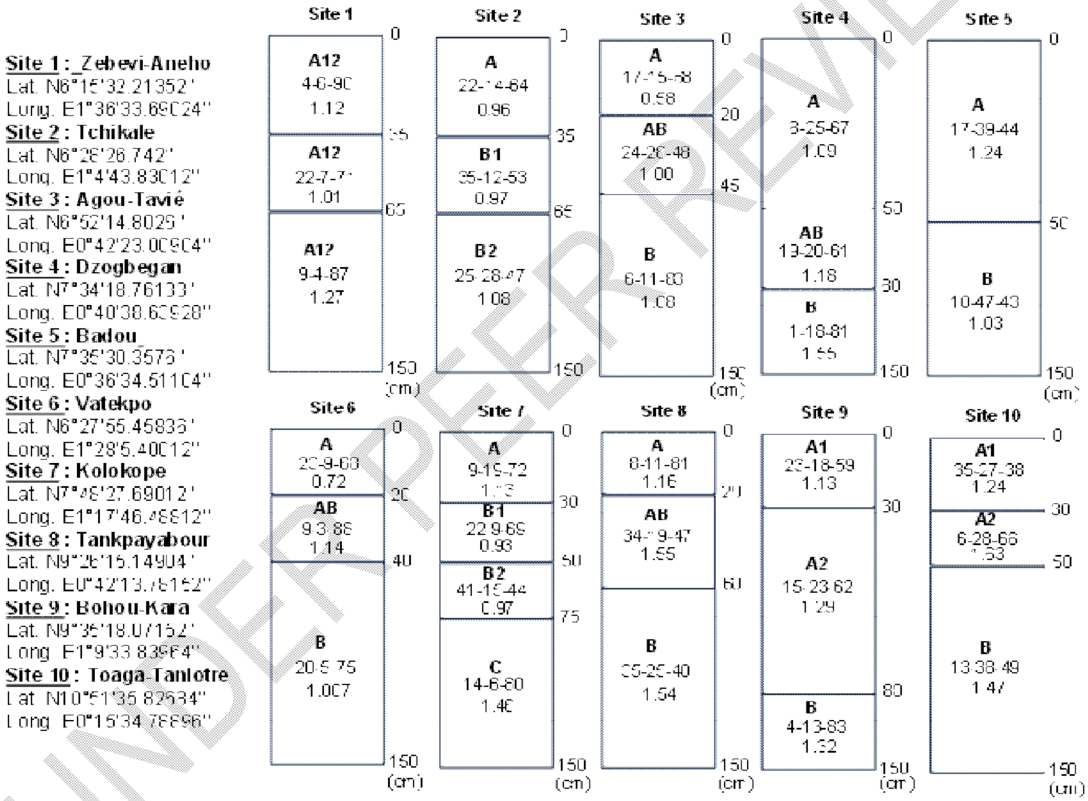

Fig. 2. Layer composition of thesoil profiles at sites 1–5 (Ferrallitic soils)and 6-10 (tropical ferruginous soils)

Soil layers are coded according their major taxonomic class ‘A’ refers to upper horizon, ‘B and C’ refer to lower horizons, textural composition (percentages clay–silt–sand in %) and bulk density (in $g.cm^{-3}$)

Table 2 : Statistical criteria resulting from differences between measured and estimated soil moisture contents

	Upper horizons				Lower horizons			
	n	ME	PSD ($cm^3.cm^{-3}$)	RMSE	n	ME	PSD ($cm^3.cm^{-3}$)	RMSE
At pF2	10	-0.013	0.077	0.078	20	-0.053	0.106	0.119

At pF4.2	10	-0.005	0.049	0.049	20	-0.002	0.077	0.077

n : number of samples ; ME: mean residual error; PSD: prediction standard deviation; RMSE: root mean squared residual error.

2.3 Estimating and spatializing the TAW

The information required for the estimation of the TAW is essentially of a pedological nature and is based on the data of [25], compiles all the descriptors of soil profiles used for the construction and characterization of the soil map of Togo. In total, data on 79 soil horizons from 23 profiles are available. The available water capacity (AWC), which represents the available water relative to a known volume of soil, was estimated (Equation 4) for each soil profile horizonfrom Class PTFs of [26]. Due to the small number of measurement points, AWC estimates are not available for three texture classes. This were therefore estimated from the values of adjacent texture classes. TAW is then calculated by multiplying the AWC by the thickness of the horizon (Equation 5). The TAW values of the different horizons of the same soil profile are then summed to give TAW of the soil profile (Equation 6). TAW for each of the major soil types is defined as the average of the TAW of the soil profiles belonging to the same major type of soil. The range of texture variation of the horizons considered covers mainly Sand, clayey sand, sandy clay, clay, clayey loam texture classes of the Aisne triangle (Figure 3). Horizons with a source rock (granitic, basaltic, gneissic), very gravelly and stony, or with continuous calcareous crust, constituting a major obstacle to the colonization of roots and to water retention, are excluded from this study. The spatialization of the TAW is done using the QGIS v 2.18.28 software, following an approach proposing a mapping of the TAW by soil type. The thematic soil map of Togo was first georeferenced, before being used to digitize the various soil layers and assign TAW values. Two maps are thus generated: Total available water map of Togo, (i) taking into account all soil horizons, (ii)of upper horizon only (cultivation horizon).

$$\boldsymbol{AWCi} = (\boldsymbol{\Theta}pF2 - \boldsymbol{\Theta}pF4.2) \qquad (\mathbf{Equation4})$$

AWCi: available water capacity of the horizon i (in mm/dm), $\boldsymbol{\Theta}$pF2: volumetric water content at FC (in mm/dm), $\boldsymbol{\Theta}$pF4.2: volumetric water content at the at WP (in mm/dm)

$$\boldsymbol{TAWi} = \boldsymbol{AWCi} * \boldsymbol{Di} \qquad (\mathbf{Equation\ 5})$$

TAWi: total available water of the horizon i (mm), Di: thickness of the horizon i (dm)

$$\boldsymbol{TAW} = \sum_{\boldsymbol{i=1}}^{\boldsymbol{n}} \boldsymbol{TAWi} \qquad (\mathbf{Équation\ 6})$$

n: number of horizons constituting the soil profile

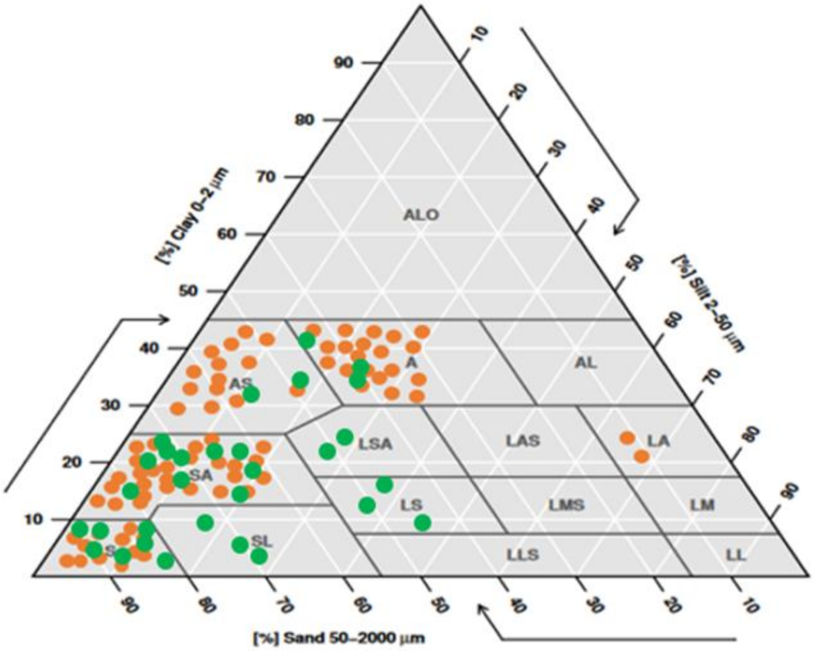

Fig. 3. Textures of the different horizons of the reference sites (in orange) and validation sites (in green) according to the triangle of textures of the Aisne

ALO: heavy clay, AS: sandy clay, A: clay, AL: silty clay, SA: clayey sand, LSA: sandy-clayey silt, LAS: clayey-sandy loam, LA: clayey loam, LA: clayey loam, S: sand, SL: silty sand, LS: sandy loam, LLS: light sandy loam, LMS; medium sandy loam, LM: medium silt, LL: light silt

3. RESULTS AND DISCUSSION

On the whole, ferrallitic soils have the highest total available water values (260 to 521.25 mm), followed by hydromorphic tropical ferruginous soils (318.1 mm), Mull soils (280.55 to 291.9 mm), halomorphic soils (188.6 mm), leached tropical ferruginous soils (88.5 to 173.7 mm), Vertisoils and paravertisoils (112.8 to 112.25 mm), hydromorphic soils (82.4 to 112.8 mm) (Figure 4). Poorly developed mineral soils have a very low available water (< 80 mm), practically zero for raw mineral soils (< 10 mm). Thus, more than 3/4 of the territory of Togo has TAW greater than 250 mm. Considering the upper horizon taken in isolation, high TAW values are observed on ferralitic soils (35.2 to 94.8 mm) and ferruginous soils (61.6 to 65.58 mm) (Figure 5).

The total available water values are a function of many pedological factors. In addition to the structural and particle size factors, which we have eliminated in this study, the total available water is very closely related to soil texture and depth. The role of the type of clay mineral is less clear, as it is absorbent but can lead to poor drainage and a compact structure. However, it appears that low total available water values are associated with predominantly sandy horizons. The total available water is also a function of the organic matter or base content. Ferralitic soils, with the highest total availablewater values, are rich in organic matter, very deep, less hard and sometimes friable, with fine textures (clayey, clayey-sandy, silty-clayey). Their gravelly loads are medium and sometimes non-existent [25].Raw mineral soils have a very low available water, mainly due to the absence of a soft horizon, and if it exists, it is shallow. They are therefore a priori unsuitable for cultivation. Only the input soils on the alluvium of wadis can be cultivated locally through irrigation. Poorly developed soils have a very low level of organic matter and low chemical fertility. They are often very stony and shallow when it comes to erosion soils, but they can be sandy and deep when it comes to input. Essentially sandy in texture, they retain little water and are therefore sensitive to wind and water erosion. Tree and food crops can be grown on these soils, provided they can be irrigated; Hence the importance of developing effective irrigation strategies on these soils.The estimation of the TAW in this study from the depth of the horizons may underestimate the volume of water actually available to crops. Indeed, in alluvial soils, crops can benefit from upwelling by capillary action from a more or less deep-water table located below the rooting depth [31]. It is estimated that capillary upwelling of the water table can cover 30 to 60% of the crop's water needs in some specific hydrogeological contexts [32].

This study provides information on soil available water at every point in Togo. These parameters can be used in agriculture, for example, to control irrigation, estimate production potential (associated with a risk of water stress), calculate the nitrogen dose for nitrogen fertilisation of a crop, estimate the risk of nitrate transfer to an aquifer..., through water balance models, crop models and mineral nitrogen leaching models. In forestry, assessment of the available water capacity of the soil is mainly used to establish water balances. Used on its own, soil available water is not a sufficient criterion for differentiating between sites, and does not provide a sound basis for choosing tree species. In fact, it only represents the soil's storage capacity, i.e. the reservoir, and does not take into account the dynamics of its emptying and filling. It is therefore essential to take into account the flow of water into and out of the site, because even a small reservoir may not be a constraint if it is regularly supplied with water due to a favourable topography. Nevertheless, by considering only the order of magnitude of the soil available water, without the compensating factor of lateral or deep water supply and particular exposure, we can deduce that no water stress is associated with species on ferralitic, hydromorphic tropical ferruginous and Mull soils, which have the total available water values of over 200 mm [33]. This constraint becomes weak to strong, with limited growth for water-demandingspecies on halomorphic soils, leached tropical ferruginous soils, Vertisols and Paravertisols, which have the total available water values of less than 200 mm; in these zones, the greater the leaf mass, the greater the risk of water stress, and thinning will be the only action by which the manager can reduce this risk.

The total available water is complex to calculate, and the method used to produce the maps is greatly simplified. For example, the level of fine particles is not taken into account, although its effect is significant [34]. Many inaccuracies or errors are expected in the basic data, due to the difficulty of assessing the required parameters. This is especialy true for textures that are determined by touch. Samples are considered unsuitable for water content measurements because soil structure is not taken into account [35], which can lead to an overestimation of water reserves [36]. Soil density data, if available, may have influenced soil water properties [37]. In addition, the transposition of results established for a given soil context to a foreign region is likely to give rise to a bias [38], even if the statistical criteria for validating the pedotransfer functions used are satisfactory. Although also omitted from the proposed method, soil organic matter richness, which is undeniable under forest cover, can influence the hydric properties of the soil horizons in which it is concentrated [39]. However, although the texture method suffers from a large number of limitations, it remains the reference method currently used in the field throughout the world [35, 40, 41]. The purpose of this inventory of inaccuracies is not to decry this method, but rather to warn potential users of its limitations and of the precautions that should accompany its implementation, particularly the interpretation of the soil available water map that has been produced. In fact, the map is primarily used to situate a site within the range of variation in soil available water and to inform the user of the risks of potential water stress. Furthermore, despite the age of the existing soil data, the mapping of the total available water generated in this study remains fully relevant, provided that the processes of pedogenesis capable of profoundly modifying the typology of a soil take time. However, the used method of spatialization (mapping by soil type) does not allow us to predict the local variability of the total available water, even though it can be very important. Indeed, the number of soil types defined can vary greatly, depending on the size of the territory and the way in which the typology is developed. These benchmarks do not locate soil types accurately enough for direct application "to the plot". This is particularly the case for the Regional Soil Reference Frameworks at a scale of 1/250000 or to 1/1000000 case of Togo. They are not necessarily exhaustive as they are sometimes limited to the most common soils. Their accuracy depends in part on the scale of mapping, and may be acceptable for scales greater than or equal to 1/50000. The accuracy of this area-based approach depends on the accuracy of the supporting soil map; this depends on the scale on which it is built, which in turn is strongly correlated with the density of boreholes per unit area. The larger the map scale (and often the smaller the extent), the greater the accuracy of the map and the more accurate the total available water estimate. This study may inspire the production of other, more pragmatic maps, with high spatial resolution and at local scales, when new soil data are available.

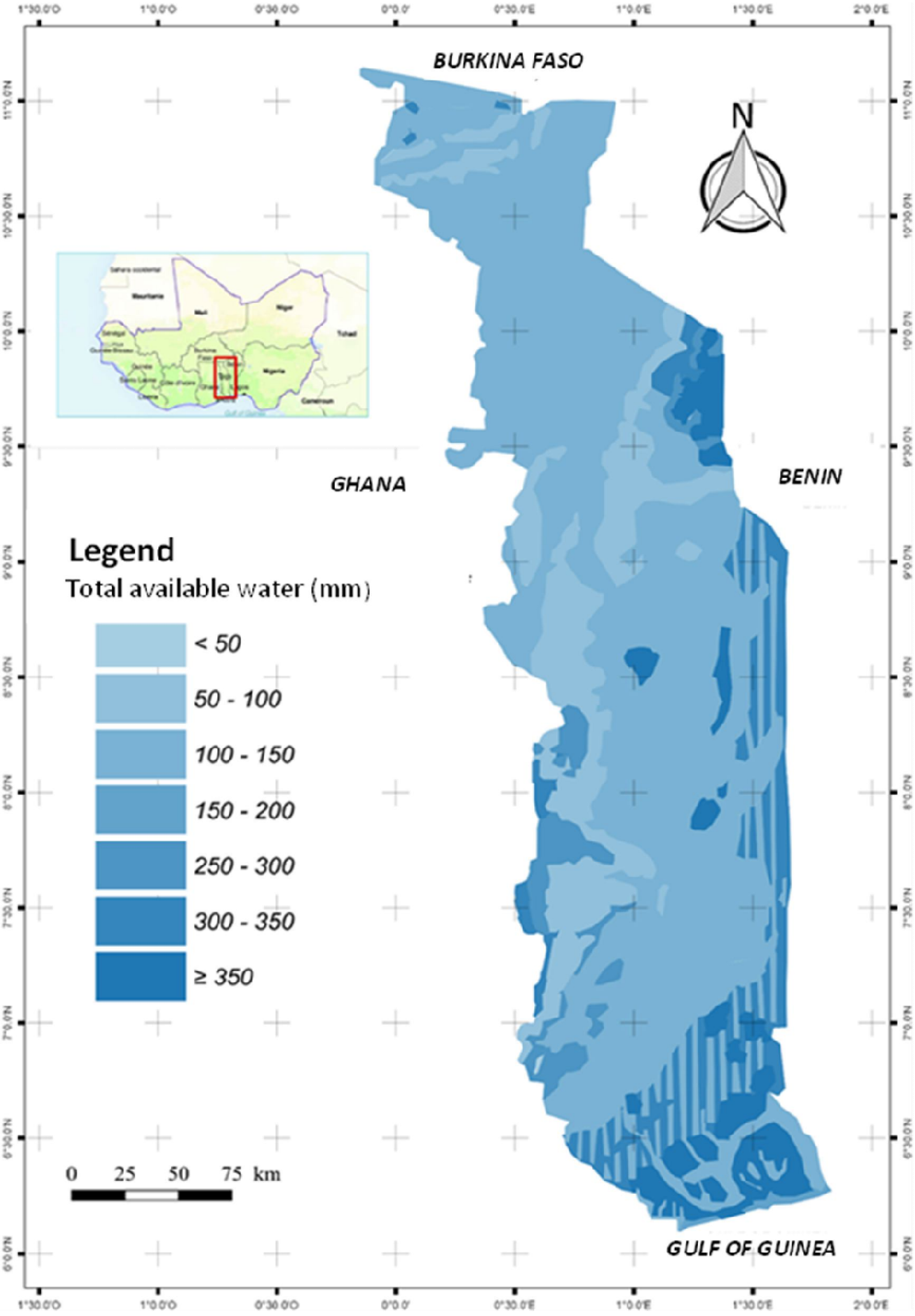

Fig. 4. Total available water map of Togo taking into account all soil horizons

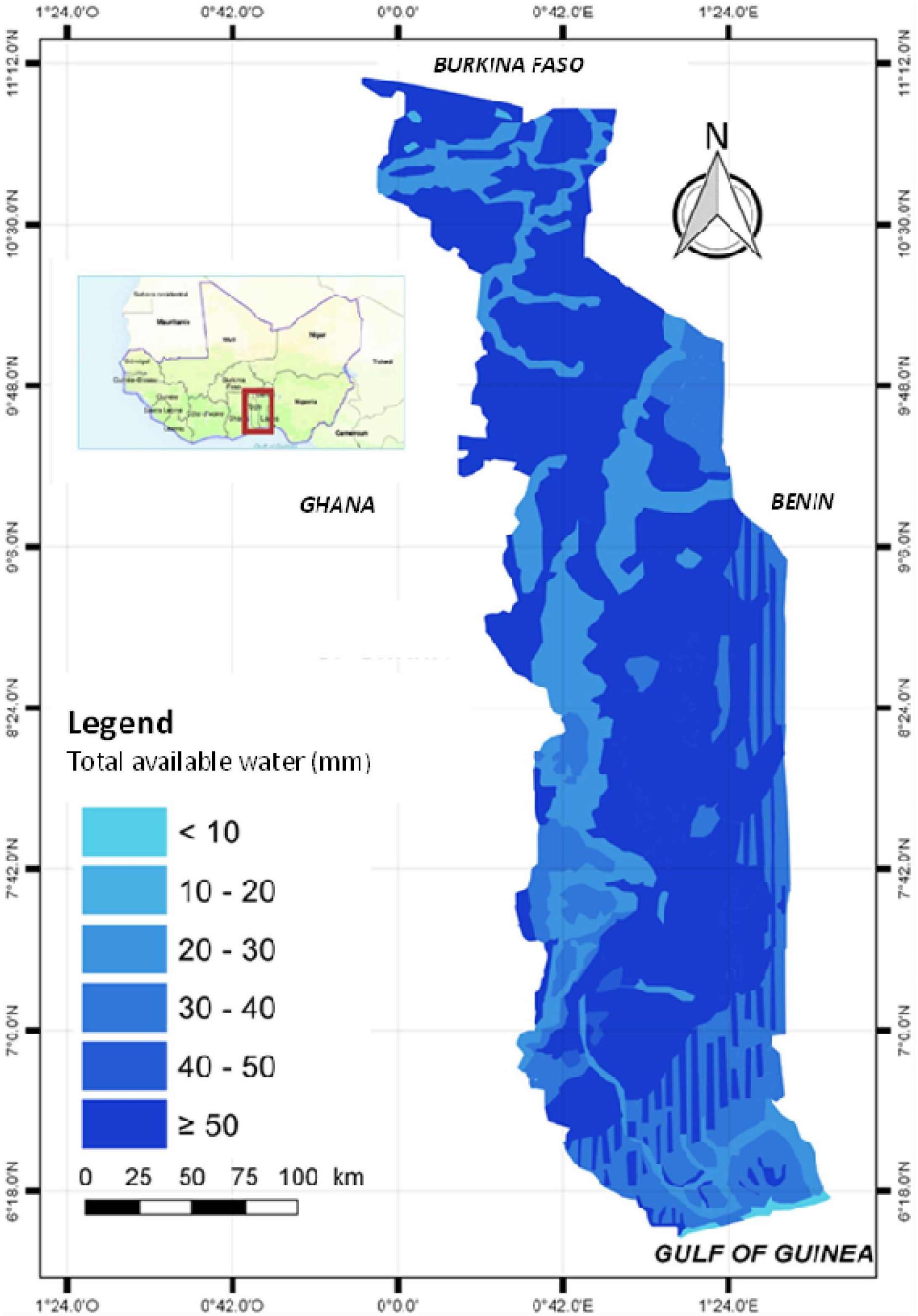

Fig. 5. Total available water map of Togo of upper horizon only

4. CONCLUSION

This work is the initial step toward characterizing water availability at a national scale in Togo. However, improvements will be needed to better account for local effects due to changes in substrates and topography. This approach is a step towards the efficient integration of water constraints in agricultural programs and forest management. The use of this map makes it possible to determine the areas where water conditions can or could become limiting depending on the requirements of the different species. Increased vigilance in these areas would make it possible to confirm or deny the risks, and to make progress in understanding the impacts of global warming on crops and forests in Togo.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

REFERENCES

1. Badjana HM, Houkpè K, Wala K, Batawila K, Akpagana K, Edjamé KS. Analysis of the temporal and spatial variability of climate series in northern Togo between 1960 and 2010. Eur. Sci. J. 2014; 10: 257-275. French
2. Koudahe K, Kayode A, Samson A, Adebola A, Djaman K. Trend Analysis in Standardized Precipitation Index and Standardized Anomaly Index in the Context of Climate Change in Southern Togo. Atmos. Clim. Sci. 2017; 7, 401-423. Doi: 10.4236/acs.2017.74030.
3. Badameli A, Dubreuil V. Diagnosis of climate change in Togo based on temperature trends between 1961 and 2010. XXVIIIth Colloquium of the International Association of Climatology. Jul 2015, Liege, Belgium. 421-426. <halshs-01176808>. French
4. TCNCC (Third National Communication on Climate Change). Third national communication of Togo under the United Nations Framework Convention on Climate Change (UNFCCC). Ministry of Environment and Forest Resources. Lomé, Togo. 2015; 160. French
5. de Jong van Lier Q, Logsdon S, Pinheiro E, Gubiani P, 2023. Plant available water. Encyclopedia of Soils in the Environment. 2023; 5: 509-515. https://doi.org/10.1016/b978-0-12-822974-3.00043-4
6. Ferreira MI. Stress Coefficients for Soil Water Balance Combined with Water Stress Indicators for Irrigation Scheduling of Woody Crops. Horticulturae. 2017; 3(2): 38. 10.3390/horticulturae3020038
7. Bhattacharya A. Chapter 3 - Water-Use Efficiency Under Changing Climatic Conditions, in: Bhattacharya A. (Ed.), Changing Climate and Resource Use Efficiency in Plants. Academic Press. 2019; 111–180. https://doi.org/10.1016/B978-0-12-816209-5.00003-9

8. de Jong van Lier Q, Wendroth O. Reexamination of the Field Capacity Concept in a Brazilian Oxisol. Soil Sci. Soc. Am. J. 2016; 80: 264-274. 10.2136/sssaj2015.01.0035
9. Logsdon S. Should Upper Limit of Available Water be Based on Field Capacity? Agrosystems Geosci. Environ. 2019; 2, Article 190066, 10.2134/age2019.08.0066
10. Minasny B, McBratney AB. Limited effect of organic matter on soil available water capacity. Eur. J. Soil Sci. 2018; 69: 39-47. 10.1111/ejss.12475
11. Raes D, Steduto P, Hsiao T, Fereres E. Chapter 2: Users guide. AquaCrop Version 6.0 – 6.1. FAO. Rome, Italy: Reference Manual. 2018; 302.
12. Kristensen JA, Balstrøm T, Jones RJA, Jones A, Montanarella L, Panagos P, Breuning-Madsen H. Development of a harmonised soil profile analytical database for Europe: a resource for supporting regional soil management. SOIL. 2019; 5 : 289-301, 10.5194/soil-5-289-2019
13. Liu H, Rezanezhad F, Lennartz B. Impact of land management on available water capacity and water storage of peatlands. Geoderma. 2022; 406, Article 115521, 10.1016/j.geoderma.2021.115521
14. Claessens H, Lejeune P, Cuvelier M, Dierstein A, Rondeux J. Development of a cartographic model for the description of forest stations in the Belgian Ardennes. Biotechnol. Agron. Soc. Environ. 2002; 6(4): 209-220.
15. Bréda N & Pieffer M. Water balance and impact of drought on the radial growth of oaks. Final Scientific Report, Inter-Regions, Forest dieback in the Rhine Valley. Nancy, France: Forest Ecophysiology Unit (INRA), ONF. 1999.
16. Grigoryan GV, Casper MC, Gauer J, Vasconcelos AC, Reiter PP. Impact of climate change on water balance of forest sites in Rhineland-Palatinate. Germany. Adv. Geosci. 2010; 27: 37-43. DOI:10.5194/adgeo-27-37-2010
17. Seynave I, Gégout J-C, Hervé J-C, Dhôte J-F, Drapier J, Bruno E, Dumé G. Picea abies site index prediction by environmental factors and understorey vegetation: a two-scale approach based on survey databases. Can. J. Forest Res. 2005; 35: 1669-1678. DOI:10.1139/x05-088.
18. Nigh GD. Impact of climate, moisture regime, and nutrient regime on the productivity of Douglas-Fir in coastal British Columbia, Canada. Clim. Change. 2006; 76(3-4): 321-337. DOI:10.1007/s10584-005-9041-y
19. Sohier C, Debruxelles J, Brusten T, Bauwens A, Claessens H, Degré A. Hydrologic modelling and dendrochronology as tool of site-species adequation assessment in a changing climate context. AMICE Project– Gembloux Agro-Bio Tech – University of Liege. In: Schüler G., Caspari T. & Seeling S., eds. ForestClim Mid-Term Conference. Nancy, France. 2010.
20. Misson L, Nicault A, Guiot J. Effects of different thinning intensities on drought response in Norway spruce [Picea abies (L.) Karst.]. Forest Ecol. Manage. 2003; 183(1-3): 47-60. DOI:10.1016/S0378-1127(03)00098-7
21. Wösten, JHM, Pachepsky YA, Rawls WJ. Pedotransfer functions: bridging the gap between available basic soil data and missing soil hydraulic characteristics. Journal of hydrology. 2001; 251(3-4): 123-150. DOI: 10.1016/S0022-1694(01)00464-4
22. Van Looy K, Bouma J, Herbst M, Koestel J, Minasny B, Mishra U, Montzka C, Nemes A, Pachepsky YA, Padarian J, Schaap MG, Tóth B, Verhoef A, Vanderborght J, van der Ploeg MJ, Weihermüller L, Zacharias S, Zhang Y, Vereecken H. Pedotransfer Functions in Earth System Science: Challenges and Perspectives. Rev. Geophys. 2017; 55: 1199–1256. https://doi.org/10.1002/2017RG000581.
23. Wösten JHM, Finke PA, Jansen MJW. Comparison of class and continuous pedotransfer functions to generate soil hydraulic characteristics. Geoderma. 1995; 66 :227–237. Doi :10.1016/00167061(94)00079-P.
24. CPCS (Commission of Pedology and Soil Mapping). Soil classification. Publ. ENSA-GRIGNON, France. 1967; 87. French.

25. Lamouroux M. Explanatory note No. 34. Soil map of Togo at 1/100000, ORSTOM Edition, Paris, France. 1969; 91. French.

26. Bruand A, Duval O, Cousin I. Estimation of soil water retention properties from the SOLHYDRO database: a first proposal combining horizon type, texture and apparent density. Étude Gestion Sols. 2004; 11(3): 323-334. https://insu.hal.science/hal-00089032.

27. Labidi A. Improving and operationalizing models for estimating the maximum useful water reserve of soils calculated from commonly measured soil characteristics. 2016; 95p. https://hal.archives-ouvertes.fr/hal-01600751. French.

28. Labidi A, Bouthier A, Cousin I. How to simply assess the Useful Reserve of a soil? Comparison of models for estimating water contents of the 2 RU boundaries using commonly measured soil characteristics. GIS GCHP2E Meetings, GIS - Large-scale Crops with High Economic and Environmental Performance (GCHP2E). FRA., Jan 2017, Paris, France. 4p. HAL Id: hal-02791625. https://hal.inrae.fr/hal-02791625. French.

29. Tranter G, Minasny B, McBratney AB. Estimating pedotransfer function prediction limits using fuzzy k-means with extragrades. Soil Science Society of America Journal. 2010; 74(6): 1967-1975. DOI: 10.2136/sssaj2009.0106

30. Vereecken H, Weynants M, Javaux M, Pachepsky Y, Schaap MG, Genuchten MT. Using pedotransfer functions to estimate the van Genuchten–Mualem soil hydraulic properties: A review. Vadose Zone Journal. 2010; 9(4): 795-820. DOI: 10.2136/vzj2010.0045

31. Ballif JL, Guérin H, Muller JC. Elements of Champagne agronomy. Knowledge of soils and their functioning. Rendzines on chalk and associated soils: geomorphological sketch. INRA Ed. 1995; 63. French

32. Vergnes JP, Decharme B, Habets F. Introduction of groundwater capillary rises using subgrid spatial variability of topography into the ISBA land surface model. Journal of Geophysical Research-Atmospheres. 2014; 119: 11065-11086. DOI :10.1002/2014JD021573

33. Baize D & Jabiol B. Guide pour la description des sols. Paris, Institut National de Recherches Agronomiques (INRA). 1995. p375. French

34. Coutadeur C, Cousin L, Nicoullaud B. Influence of the stony phase on soil water reserves. Etude et Gestion des Sols. 2000; 7(3): 191-205. French

35. Bruand A, Duval O, Gaillard H, Darthout R, Jamagne M. Variability in the water retention properties of soils: the importance of bulk density. Etude Gestion Sols. 1996; 3(1): 27-40. French

36. Trouche G & Morlon P. Comparison of different methods for estimating the soil available water (SAW) within the perimeter of the O.G.A.F. Environnement in the Migennes area (Yonne). Etude Gestion Sols. 1999; 6(1) : 41-54. French

37. Quentin C, Bigorre F, Bréda N, Granier A, Tessier D. Study of the soils of the Hesse Forest (Lorraine). Contribution to the study of the water balance. Etude Gestion Sols. 2001; 8(4): 215-229. French

38. Al Majou H, Bruand A, Duval O, Cousin I. Comparison of national and European pedotransfer functions to predict soil water retention properties. Etude Gestion Sols. 2007; 14(2): 103-116. French

39. Bigorre F, Tessier D, Pédro G. How clay and organic matter contribute to water retention properties. Significance of CEC and surface area of soils. C.R. Acad. Sci. Paris - Earth Planet. Sci. 2000; 330(4): 245-250.

40. Bréda N, Lefèvre Y, Badeau V. Water reserves in temperate forest soils: specific features and assessment difficulties. Houille Blanche. 2002; 3: 24-32. French

41. Dridi B & Zemmouri S. Pedotransfer functions for Vertisols of the Mitidja plain (Algeria): search for the most relevant parameters for water retention. Biotechnol. Agron. Soc. Environ. 2012; 16(2): 193-201. French

SUPPORTING INFORMATION

Typical soil moisture content by textural class according to Bruand *et al*. (2004)

Textural class	ϴpF2 (cm^{3}.cm^{-3})	ϴpF4 .2 (cm^{3}.cm^{-3})	AWC (mm.dm^{-1})
	Horizon A		
ALO	0.373	0.249	12.4
AL	0.333	0.197	13.6
AS	0.385	0.212	17.3
A	-	-	-
LA	0.325	0.152	17.3
LAS	0.320	0.153	16.7
LSA	0.283	0.140	14.3
LM	0.322	0.109	21.3
LMS	0.300	0.117	18.3
LS	0.265	0.104	16.1
LLS / LL	-	-	-
SA	0.259	0.131	12.8
SL	0.217	0.084	13.3
S	0.117	0.057	6
	Horizon E, B, C		
ALO	0.408	0.297	11.1
AL	0.335	0.222	11.3
AS	0.296	0.201	9.5
A	0.315	0.221	9.4
LA	0.312	0.163	14.9
LAS	0.304	0.156	14.8
LSA	0.262	0.158	10.4
LM	0.321	0.114	20.7
LMS	0.330	0.129	20.1
LS / LLS /LL	-	-	-
SA	0.239	0.136	10.3
SL	0.201	0.085	11.6
S	0.110	0.037	7.3

ALO: heavy clay, AS: sandy clay, A: clay, AL: silty clay, SA: clayey sand, LSA: sandy-clayey silt, LAS: clayey-sandy loam, LA: clayey loam, LA: clayey loam, S: sand, SL: silty sand, LS: sandy loam, LLS: light sandy loam, LMS; medium sandy loam, LM: medium silt, LL: light silt

Summary of soil data according to Lamouroux (1969) and estimation of the available water of different soil types in Togo

Soil type	Profile number	Horizon	Thickness (dm)	Texture	AWC_i estimated from the Class PTFs of [20] ($mm.dm^{-1}$)	TAW_i (mm)	TAW (mm)	
Class I - Raw mineral soils								
I_1	1	A	< 1	S	6	< 6	< 6	< 6
$I_{2,}$	1	A	< 1	S	6	< 6	< 6	
I_3	1	A	< 1	S	6	< 6	< 6	
Class II – Less developed soils								
II_1, II_2	1	A	3.5	S	6	21	51.9	63.7
		C	3	SA	10.3	30.9		
II_3	1	A	1.2	S	6	7.2	75.5	
		AB	2.8	S	6	16.8		
		B	5	SA	10.3	51,5		
Class III - Vertisoils et Paravertisoils								
III_1	1	A	1	A	9.4	9.4	112.8	112.525
		AB	1.5	A	9.4	14.1		
		B	9.5	A	9.4	89.3		
III_2	1	A	1.1	AS	17.3	19.03	112.25	
		AB	2.4	AS	17.3	41.52		
		B	3.3	A	9.4	31.02		
		B	2.2	A	9.4	20.68		
		*C	8	-	-	-		
Class VI – Mull soils								
VI_1	1	A	1	SA	12.8	12.8	280.55	286.225
		B_1	1.5	AS	9.5	14.25		
		B_2	5	AS	9.5	47.5		
		C	20	SA	10.3	206		
VI_2	1	A	2.5	SA	12.8	32	291.9	
		B_1	5.5	A	9.4	51.7		
		$B_{(2.1)}$	8	A	9.4	75.2		
		$B_{(2.2)}$	14	AS	9.5	133		
Class VIII - Soils with sesquioxides and rapidly mineralized organic matter Leached tropical ferruginous soils, more or less indurated and more or less hydromorphic at depth								
$VIII_1$ à $VIII_6$	1	A_1	2.5	SA	12.8	32	149.5	135.66
		B_1	4	A	9.4	37.6		
		B_2	8.5	A	9.4	79.9		
	2	A	1.5	S	6	9	88.5	
		AB	2.5	SA	12.8	32		
		B	5	AS	9.5	47.5		

	3	A	1.5	SA	12.8	19.2	133.6	
		AB	2.5	SA	12.8	32		
		B	2	SA	10.3	20.6		
		BC$_0$	6	SA	10.3	61.8		
	4	A1	2	S	6	12	133	
		A2	3	S	6	18		
		B	10	SA	10.3	103		
	5	A	3	S	6	18	173.7	
		A	9	AS	17.3	155.7		
Class VIII - Soils with sesquioxides and rapidly mineralized organic matter Hydromorphic tropical ferruginous soils (pseudogley at depth)								
VIII$_7$	1	A$_1$	4.2	S	6	25.2	318.1	318.1
		A$_2$	1.8	S	6	10.8		
		A$_2$B	2	SA	12.8	25.6		
		B$_1$C0	3.5	AS	9.5	33.25		
		B$_2$	5.5	AS	9.5	52.25		
		C	18	AS	9.5	171		
Class VIII - Soils with sesquioxides and rapidly mineralized organic matter Ferrallitic soils								
VIII$_8$ à VIII$_{12}$	1	A	2	SA	12.8	25.6	348.9	349.74
		AB	1	SA	12.8	12.8		
		B$_1$	4	AS	9.5	38		
		B$_2$C$_0$	8	A	9.4	75.5		
		B$_3$	10	A	9.4	94		
		C	10	SA	10.3	103		
	2	A	2.5	SA	12.8	32	521.25	
		B	22.5	SA	10.3	231.75		
		C	25	SA	10.3	257.5		
VIII$_{13}$	1	A	2	SA	12.8	25.6	332.45	
		AB	4	AS	17.3	69.2		
		B1	3.5	AS	9.5	33.25		
		B2	7.5	A	9.4	70.5		
		C	13	SA	10.3	133.9		
VIII$_{14}$	1	A	1.2	SA	12.8	15.36	285.6	
		AB	1.8	SA	12.8	23.04		
		B	15	SA	10.3	154.5		
		BC	5	SA	10.3	51.5		
		C	4	SA	10.3	41.2		
VIII$_{15}$	1	A$_0$	0.2	LA	17.3	3.46	260.5	
		A	2.3	LA	17.3	39.79		
		B	5.5	SA	10.3	56.65		
		C$_1$	22	S	7.3	160.6		

		*C_2	20	-	-	-		
Class IX – Halomorphic soils								
IX_1		A	0.7	A	9.4	6.58	188.6	188.6
		B_1	6.3	A	9.4	59.22		
		B_2	7	A	9.4	65.8		
		BC	6	AS	9.5	57		
Class X – Hydromorphic soils								
X_1		nd	nd	nd	-	-	≈112.8	105.2
X_2 et X3	1	A	1.5	A	9.4	14.1	112.8	
		AB	1	A	9.4	9.4		
		B1	2.5	A	9.4	23.5		
		B2	5	A	9.4	47		
		BC	2	A	9.4	18.8		
	2	A	2.5	SA	10.3	25.75	82.4	
		B	3.5	SA	10.3	36.05		
		C	2	SA	10.3	20.6		

*: source rock; nd: not determined; A: clayey; S: sandy; SA: sandy-clayey, AS: clayey-sandy, LA: silty-clayey

Class I - Raw mineral soils
I_1, I_2: Raw mineral soils from erosion on various hard rocks: *Lithosols*
I_3 : Raw mineral soils
Classe II – Less developed soils
II1, II2: Soils with little erosion on acidic or basic rocks
II3: Poorly developed soils, on filler materials
Class II – Poorly developed soils
II_1, II_2: Soils with little erosion on acidic or basic rocks
II_3: Poorly developed soils, on filler materials
Class III - Vertisols and Paravertisols
III_1: Vertisols and paravertisols, topomorphic or lithotopomorphic
III_2: Lithomorphic Vertisols and Paravertisols
Class VI - Mull Soils
VI_1: Modal eutrophic brown soil (Dapango series)
VI_2: Eutrophic, hydromorphic brown soil (Tomegbé Series)
Class. VIII - Soils with sesquioxides and rapidly mineralized organic matter
$VIII_1$ to $VIII_6$: Leached tropical ferruginous soils, with concretions and cuirasses
$VIII_1$: on sandstone schists
$VIII_2$: On granites
$VIII_3$**:** On gneiss and granito-gneiss
$VIII_4$: On quartzitic rocks
$VIII_5$: On sericitic shales and jaspers
$VIII_6$: On undifferentiated Rocks
$VIII_7$: Hydromorphic tropical ferruginous soils (pseudogley at depth)
$VIII_8$ **to** VII_{15}: Ferrallitic soils
$VIII_8$: Weakly modal ferrallitic soils on basic rocks
$VIII_9$: Weakly modal ferrallitic soils on sandy-clay sediments
$VIII_{10}$: Weakly ferrallitic soils with concretions and armors on gneiss
$VIII_{11}$: Weakly ferrallitic soils with concretions and cuirasses on basic rocks
$VIII_{12}$: Weakly ferrallitic soils - Intergrade to tropical ferruginous soils, on undifferentiated rocks
$VIII_{13}$: Typical modal ferralitic soils on mica schists
$VIII_{14}$: Typical modal ferralitic soils on interbedded quartzite with mica schists
$VIII_{15}$: Typical modal ferralitic soils on undifferentiated colluvium
Class IX - Halomorphic soils
IX_1: Salty to alkaline soils
IX_2: Solodized Solonetz
Class X - Hydromorphic soils
X_1: Hydromorphic, moderately organic, gley soils
X_2: Hydromorphic mineral soils, with gley and/or pseudogley of all or depth, on various alluvial deposits
X_3: Hydromorphic mineral soils, with gley and/or pseudogley of ensemble or depth, on sandy colluviu