

# Original Research Article

## Plant available water estimated by using pedotransfer function classes to improve consideration of 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 defined as the difference between the water content at field capacity and at wilting point. It's 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 tree 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. 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. 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  $\frac{3}{4}$  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.

*Keywords: Plant available water; total available water; field capacity; wilting point; pedotransfer function class.*

### 1. INTRODUCTION

Climate change scenarios in Togo show that the country is projected to experience unprecedented warming for a little increase in precipitation between 2025 and 2100 [1]. The climate is likely to become drier as temperatures rise faster than precipitation and the additional amount of rainfall is too small to compensate the increase in evapotranspiration

resulting from high temperature increases. Thus, all natural ecosystems, i.e. natural forests and wooded savannahs, would no longer exist by 2100.

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 [2]. Not all soil water is available to plants, and plant available water (PAW) can be expressed as a fraction of total soil water storage [3, 4]. 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 [5, 6]. 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 [7, 8, 9, 10].

The water supply of crops is one of the major variables influencing their productivity and the quality of the products obtained. 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 stations to water stress and to more precise management recommendations regarding the choice of species to be planted and forestial techniques [11]. 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 [12], the definition of the suitability of sites for forestry of different species by an assessment of water risk associated with them [13]. 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 [14, 15]. 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 [16]. 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 [17]. 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 stations in Togo for use by field foresters. These will be keys to determining the trophic level of soils and water availability of the stations. 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 useful soil water reserves in Togo. This study aims to quantify water availability of Togo soils, using the texture method, in direct connection with Togo soil data, with the objective of improving the consideration of water constraints 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 [18]. 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  $\frac{3}{4}$  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 [19] on the basis of 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 Evaluation of the applicability and performance of the pedotransfer function used

At present, no Class PTFs has been identified that is 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 [20]. It was selected on the basis of their precision and of available pedological data (Figure 1) [21, 22], 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 carried out 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 lower soil 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 FPT [23], by calculating the applicability percentage (AP). AP is the percentage of samples examined with texture and structure parameters (bulk density) within the limits of those of the calibration samples. As AP obtained (91,11 %) was greater than 85 % (Table 1), the chosen PTFs of [20] was maintained for the study. To assess the performance of FPTs, three statistical criteria were applied: mean residual error (ME) and associated prediction standard deviation (PSD), and root mean squared residual error (RMSE). 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  $\theta$ , whereas if it is negative, they underestimate it. PSD (Equation 2) is used to estimate the precision of the estimate, which is more precise the closer PSD is to zero. 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 FPT with an RMSE greater than 0.09 cm<sup>3</sup>.cm<sup>-3</sup> is considered inaccurate and should therefore be rejected [24, 25]. All these statistical criteria calculated (Table 2) validate the use of PTFs of [20].

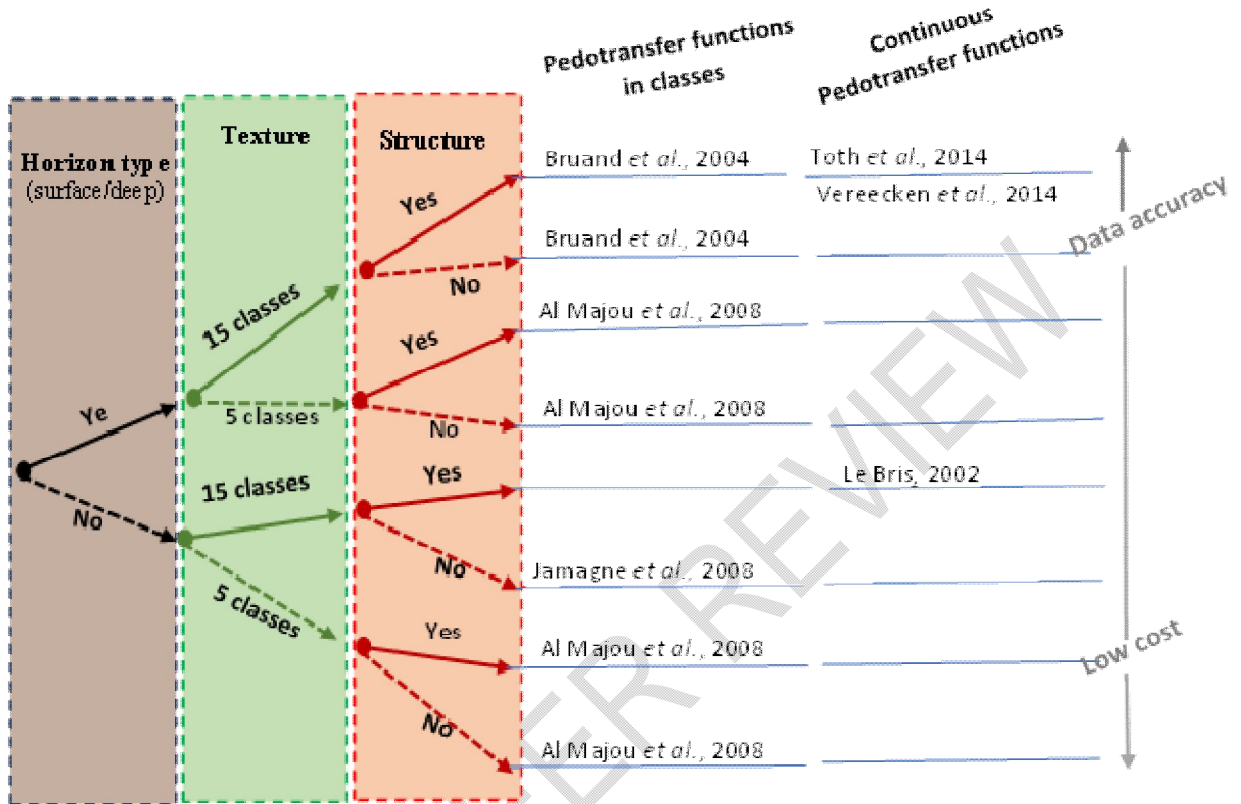


Fig.1. Decision tree for selecting a pedotransfer function based on available data [21]

Table 1. Value of applicability percentage (ap) of the class PTFs of [20]

Textural class	Clay	Silt	Sand	Bulk density	AP (%)
Current study	1.0-41.0	-	38.0-90.0	0.58-1.63	-
Bruand et al. (2004)	1.9-92.9	nd	1.1-90.1	1.1-1.8	88.88

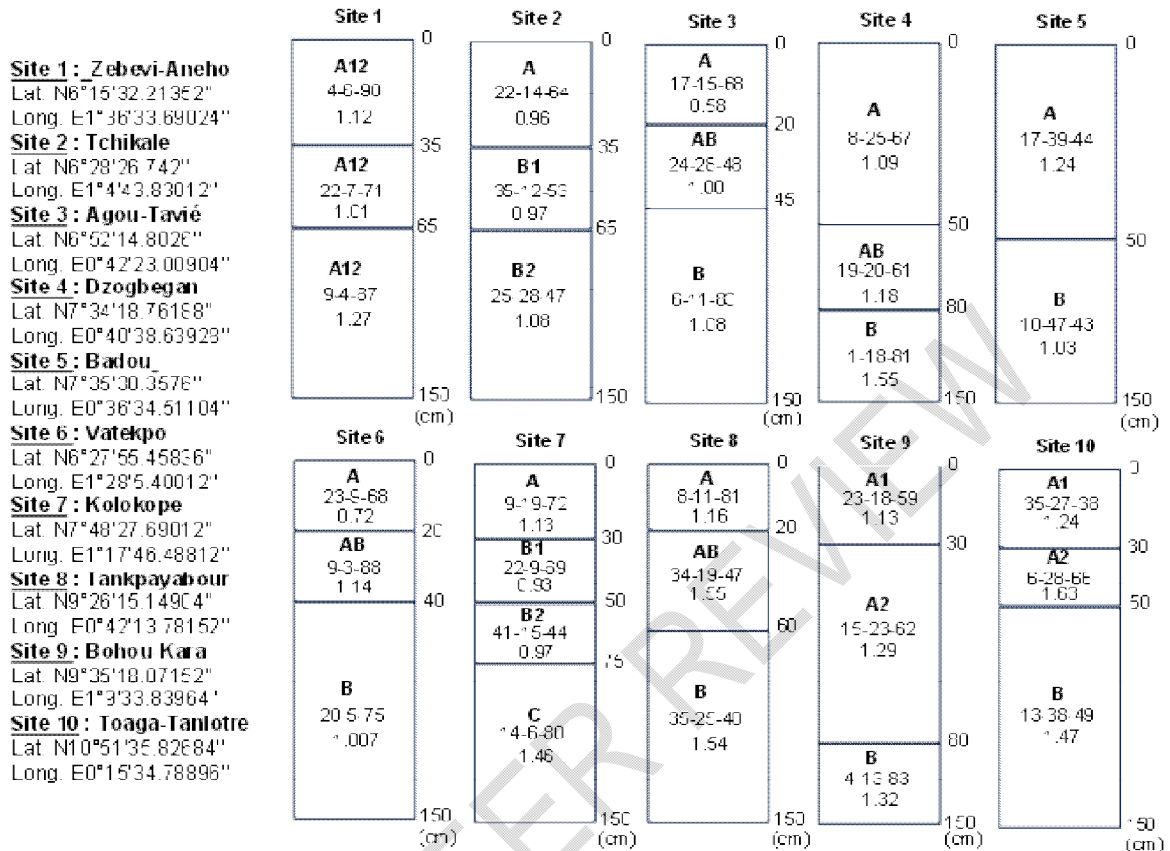
n: number of samples

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

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

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

n: number of samples,  $\theta_e$ : estimated soil moisture content ( $\text{cm}^3 \cdot \text{cm}^{-3}$ ),  $\theta_m$ : measured soil moisture content ( $\text{cm}^3 \cdot \text{cm}^{-3}$ ).



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

Soil layers are coded according to their major taxonomic class 'A' refers to upper horizon, 'B' and 'C' refer to lower horizons, textural composition (percentages clay–silt–sand) and bulk density

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

	Topsoil layers				Subsoil layers			
	n	ME	PSD (cm <sup>3</sup> .cm <sup>-3</sup> )	RMSE	n	ME	PSD (cm <sup>3</sup> .cm <sup>-3</sup> )	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

### 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 [19], which 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 an elementary volume of soil, was estimated (Equation 4) for each soil profile horizon from Class PTFs of [20] (Table 3). Due to the small number of measurement points, AWC estimates are not available for three texture classes. These 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).

$$AWCi = (\theta_{pF2} - \theta_{pF4.2}) \quad (\text{Equation 4})$$

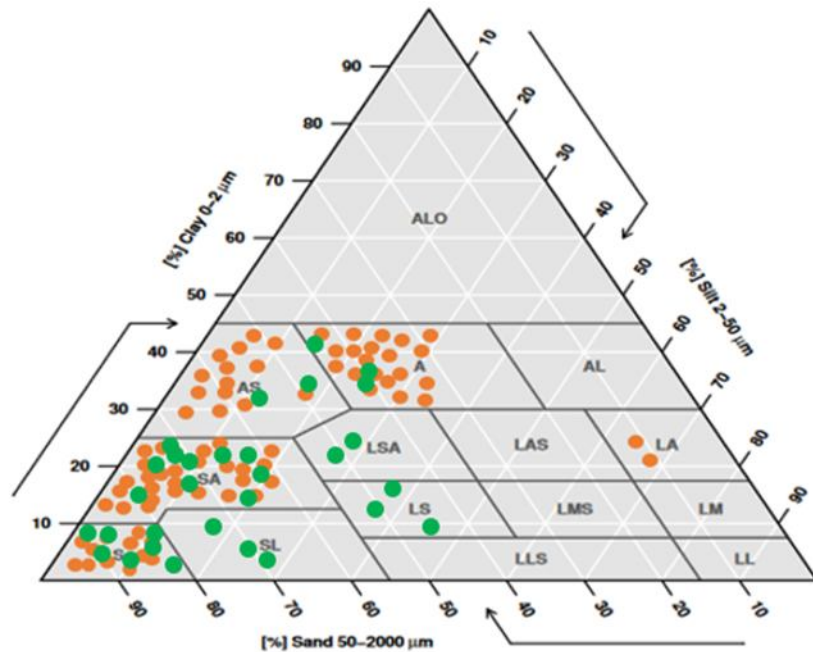
AWCi: available water capacity of the horizon i (in mm/dm),  $\theta_{pF2}$ : volumetric water content at FC (in mm/dm),  $\theta_{pF4.2}$ : volumetric water content at the at WP (in mm/dm)

$$TAWi = AWCi * Di \quad (\text{Equation 5})$$

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

$$TAW = \sum_{i=1}^n TAWi \quad (\text{Equation 6})$$

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

**Table 3. Typical soil moisture content by textural class according to Bruand *et al.* (2004)**

Textural class	$\Theta_{pF2} (\text{cm}^3 \cdot \text{cm}^{-3})$	$\Theta_{pF4.2} (\text{cm}^3 \cdot \text{cm}^{-3})$	AWC ( $\text{mm} \cdot \text{dm}^{-1}$ )
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

### 3. RESULTS AND DISCUSSION

On the whole, ferrallitic soils have the highest TAW values (260 to 521.25 mm), followed by hydromorphic tropical ferruginous soils (318.1 mm), Mull soils (280.55 to 291.9 mm), halomorph soils (188.6 mm), leached tropical ferruginous soils (88.5 to 173.7 mm), Vertisols and paravertisols (112.8 to 112.25 mm), hydromorphic soils (82.4 to 112.8 mm) (Table 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 (Figure 4). Considering the upper horizon taken in isolation, high TAW values are observed on ferrallitic soils (35.2 to 94.8 mm) and ferruginous soils (61.6 to 65.58 mm) (Figure 5).

TAW values are a function of many pedological factors. In addition to the structural and particle size factors, which we have eliminated in this study, TAW 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 TAW

values are associated with predominantly sandy horizons. The TAW is also a function of the organic matter or base content. Ferralitic soils, with the highest TAW 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 [19].

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 [26]. 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 [27].

The variability factors of the TAW are mainly the geology and relief, through their influence on soil depth, texture and coarse element load. Indeed, many factors, both natural and biological, influence the pedogenetic processes that mark and characterize soils to a greater or lesser extent. Based on the main processes of pedogenesis (ferrallitization, ferruginization, leaching and leaching, sesquioxide induration, reworking, hydromorphism, argillification, alkalization and salinization, carbonation), the current typology of soils in Togo has evolved, modifying their useful water reserve to a greater or lesser extent. Therefore, a new soil characterization is necessary, since the only soil data available to date and considered in this study date back about half a century. In addition, the TAW is complex to calculate, and the method used to produce the maps is greatly simplified. Thus, the level of fine particles is not taken into account, although its effect is significant. At the level of the basic data, many inaccuracies or errors are expected due to the difficulty of evaluating the required parameters. This is especially true for textures that are determined by touch. On the other hand, the pedotransfer classes used to transform texture data into water-holding capacity only allow a fairly rough estimate.

In addition, the used method of spatialization (mapping by soil type) does not allow us to predict the local variability of the TAW, 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 TAW estimate. Thus, it is not recommended to use this map to study the spatial variability of TAW at very local scales (massif, forest). Other more pragmatic maps

can be produced at high spatial resolution and at local scales, when actual depth and fine  
particle load data are available.

UNDER PEER REVIEW

Table 4. 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 <sub>i</sub> estimated from the Class PTFs of [20] (mm.dm <sup>-1</sup> )	TAW <sub>i</sub> (mm)	TAW (mm)
Class I - Raw mineral soils							
I <sub>1</sub>	1	A	< 1	S	6	< 6	< 6
I <sub>2</sub>	1	A	< 1	S	6	< 6	
I <sub>3</sub>	1	A	< 1	S	6	< 6	
Class II - Less developed soils							
II <sub>1</sub> , II <sub>2</sub>	1	A	3.5	S	6	21	51.9
		C	3	SA	10.3	30.9	
II <sub>3</sub>	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 - Vertisols et Paravertisols							
III <sub>1</sub>	1	A	1	A	9.4	9.4	112.8
		AB	1.5	A	9.4	14.1	
		B	9.5	A	9.4	89.3	
III <sub>2</sub>	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 <sub>1</sub>	1	A	1	SA	12.8	12.8	280.55
		B <sub>1</sub>	1.5	AS	9.5	14.25	
		B <sub>2</sub>	5	AS	9.5	47.5	
		C	20	SA	10.3	206	
VI <sub>2</sub>	1	A	2.5	SA	12.8	32	291.9
		B <sub>1</sub>	5.5	A	9.4	51.7	
		B <sub>(2,1)</sub>	8	A	9.4	75.2	
		B <sub>(2,2)</sub>	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 <sub>1</sub> à VIII <sub>6</sub>	1	A <sub>1</sub>	2.5	SA	12.8	32	149.5
		B <sub>1</sub>	4	A	9.4	37.6	
		B <sub>2</sub>	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	135.66

	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 <sub>0</sub>	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 <sub>7</sub>	1	A <sub>1</sub>	4.2	S	6	25.2	318.1	318.1
		A <sub>2</sub>	1.8	S	6	10.8		
		A <sub>2</sub> B	2	SA	12.8	25.6		
		B <sub>1</sub> C <sub>0</sub>	3.5	AS	9.5	33.25		
		B <sub>2</sub>	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 <sub>8</sub> à VIII <sub>12</sub>	1	A	2	SA	12.8	25.6	348.9	
		AB	1	SA	12.8	12.8		
		B <sub>1</sub>	4	AS	9.5	38		
		B <sub>2</sub> C <sub>0</sub>	8	A	9.4	75.5		
		B <sub>3</sub>	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 <sub>13</sub>	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 <sub>14</sub>	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 <sub>15</sub>	1	A <sub>0</sub>	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 <sub>1</sub>	22	S	7.3	160.6		

		*C <sub>2</sub>	20	-	-	-		
Class IX – Halomorphicsoils								
IX <sub>1</sub>		A	0.7	A	9.4	6.58	188.6	188.6
		B <sub>1</sub>	6.3	A	9.4	59.22		
		B <sub>2</sub>	7	A	9.4	65.8		
		BC	6	AS	9.5	57		
Class X – Hydromorphicsoils								
X <sub>1</sub>		nd	nd	nd	-	-	≈112.8	105.2
X <sub>2</sub> et X <sub>3</sub>	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<sub>1</sub>, I<sub>2</sub>: Raw mineral soils from erosion on various hard rocks: *Lithosols*  
I<sub>3</sub>: Raw mineralsoils

**Classe II – Lessdevelopedsoils**

II<sub>1</sub>, II<sub>2</sub>: Soils with little erosion on acidic or basic rocks  
II<sub>3</sub>: Poorly developed soils, on filler materials

**Class II – Poorly developed soils**

II<sub>1</sub>, II<sub>2</sub>: Soils with little erosion on acidic or basic rocks  
II<sub>3</sub>: Poorly developed soils, on filler materials

**Class III - Vertisols and Parvertisols**

III<sub>1</sub>: Vertisols and parvertisols, topomorphic or lithotopomorphic  
III<sub>2</sub>: Lithomorphic Vertisols and Parvertisols

**Class VI - Mull Soils**

VI<sub>1</sub>: Modal eutrophic brown soil (Dapango series)  
VI<sub>2</sub>: Eutrophic, hydromorphic brown soil (Tomegbé Series)

**Class. VIII - Soils with sesquioxides and rapidly mineralized organic matter**

VIII<sub>1</sub> to VIII<sub>6</sub>: Leached tropical ferruginous soils, with concretions and cuirasses  
VIII<sub>1</sub>: on sandstone schists  
VIII<sub>2</sub>: On granites  
VIII<sub>3</sub>: On gneiss and granito-gneiss  
VIII<sub>4</sub>: On quartzitic rocks  
VIII<sub>5</sub>: On sericitic shales and jaspers

VIII<sub>6</sub>: On undifferentiated Rocks

VIII<sub>7</sub>: Hydromorphic tropical ferruginous soils (pseudogley at depth)

VIII<sub>8</sub> to VIII<sub>15</sub>: Ferrallitic soils

VIII<sub>8</sub>: Weakly modal ferrallitic soils on basic rocks

VIII<sub>9</sub>: Weakly modal ferrallitic soils on sandy-clay sediments

VIII<sub>10</sub>: Weakly ferrallitic soils with concretions and armors on gneiss

VIII<sub>11</sub>: Weakly ferrallitic soils with concretions and cuirasses on basic rocks

VIII<sub>12</sub>: Weakly ferrallitic soils - Intergrade to tropical ferruginous soils, on undifferentiated rocks

VIII<sub>13</sub>: Typical modal ferrallitic soils on mica schists

VIII<sub>14</sub>: Typical modal ferrallitic soils on interbedded quartzite with mica schists

VIII<sub>15</sub>: Typical modal ferrallitic soils on undifferentiated colluvium

**Class IX - Halomorphics soils**

IX<sub>1</sub>: Salty to alkaline soils

IX<sub>2</sub>: Solodized Solonetz

**Class X - Hydromorphic soils**

X<sub>1</sub>: Hydromorphic, moderately organic, gley soils

X<sub>2</sub>: Hydromorphic mineral soils, with gley and/or pseudogley of all or depth, on various alluvial deposits

X<sub>3</sub>: Hydromorphic mineral soils, with gley and/or pseudogley of ensemble or depth, on sandy colluvium

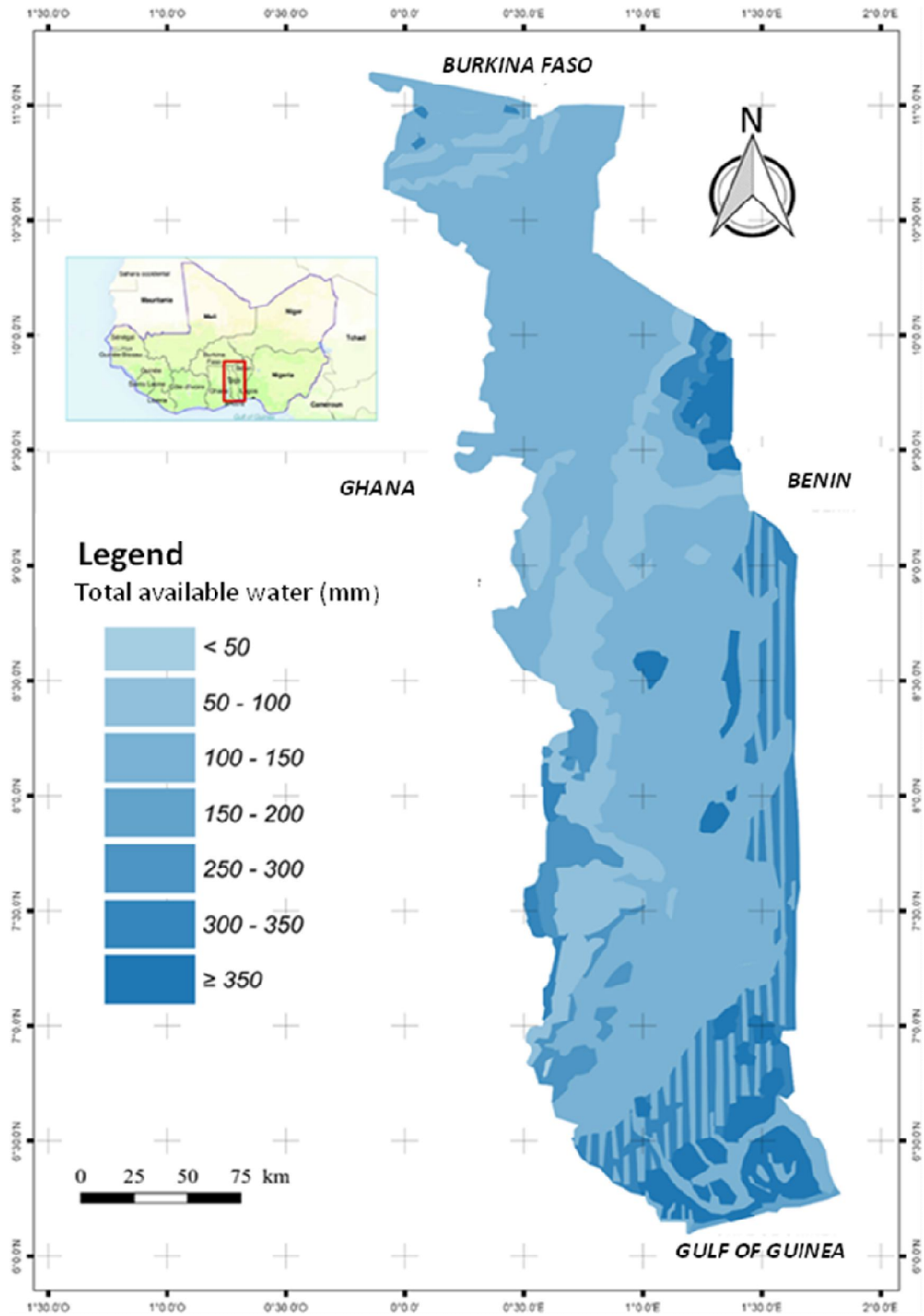


Fig. 4. Total available water map of Togo taking into account all soil horizons

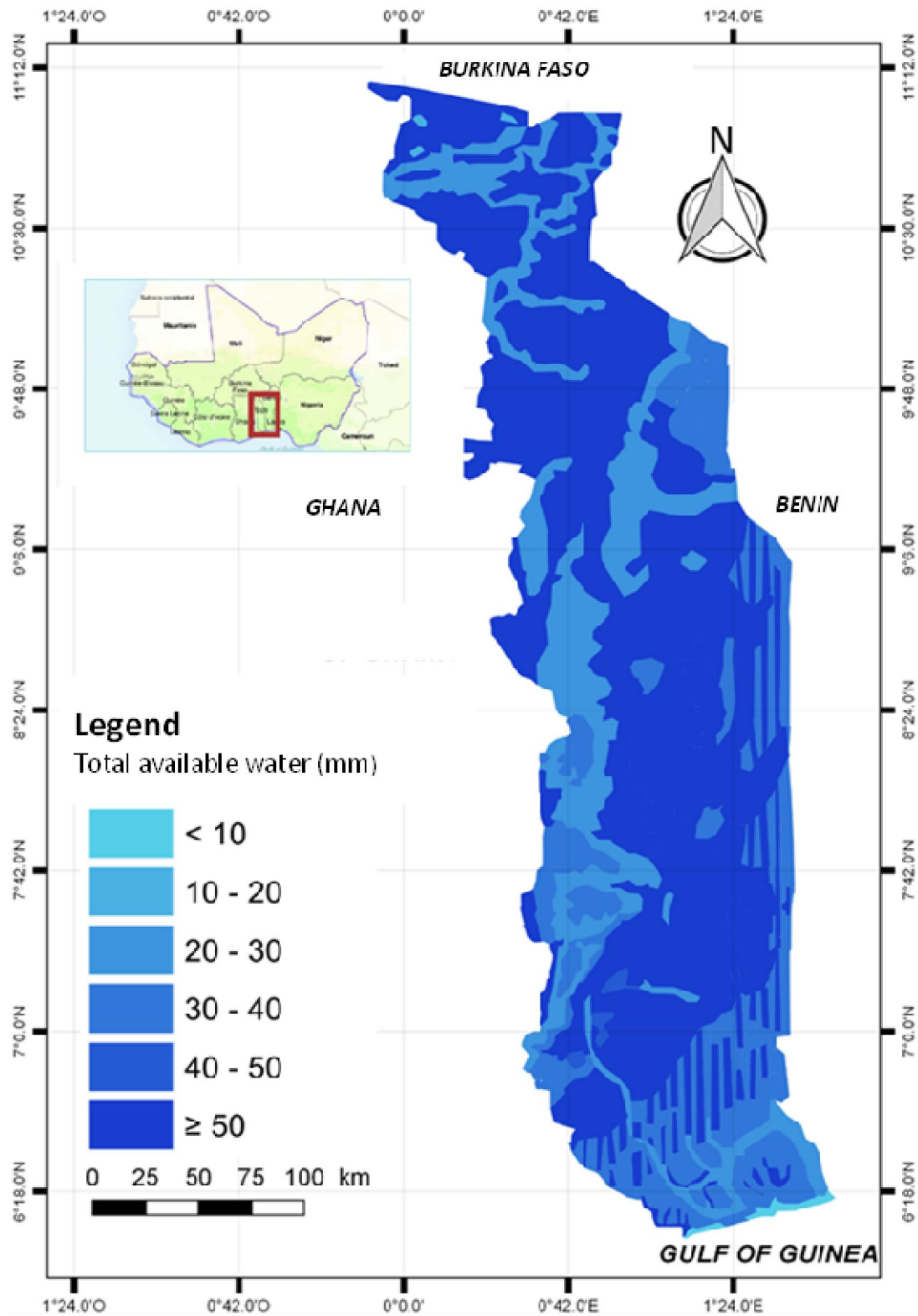


Fig. 5. Total available water map of Togo of upper horizon only (cultivation horizon)

## 4. CONCLUSION

This work is a first step that demonstrates the possibility of producing maps characterizing the water resource available to plants in Togo, while having local relevance. 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. It also makes it possible to better determine the water content ranges of soils favorable to different species. While it is becoming possible to simulate the evolution of water stock in the soil under different climate change assumptions, it should not be forgotten that water availability is not the only parameter determining the distribution or growth of plant species. The effects of temperature changes as well as parameters for characterizing soil nutrition must also be taken into account. Thus, it remains difficult to draw conclusions about the vulnerability of tree species to climate change. 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.

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