Confronting the available water content indicator to forest soils: the example from the Haut-Languedoc (France).

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Highlight:

- The soil available water content (SAWC) calculation needs specific adjustments when applied to forest soils.
- The considered soil volume is the main driver of SAWC
- The soil coarse fraction contains available water for plant, and this amount of water must be considered in soil available water content assessment.
- Specific pedotransfert functions are needed for the fine earth water retention assessment of forest soils.

Abstract:

Soil available water content (SAWC) is becoming a crucial issue for forest management in the context of climate changes. Nevertheless, SAWC indicator which was created for agricultural soils needs specific adaptations when it is estimated for forest soils. This study aimed to find the best way to apply the SAWC indicator with regard to its significance for explaining variations of tree fertility across a given region. An extensive study over a spatial sampling of

100 Douglas-fir stand plots was conducted in the Haut Languedoc Regional Nature Parc (Southern France). It involved stand fertility assessments, morphological observations of deep soil pits including the saprolite, quantitative estimations of coarse fragments, texture and organic matter laboratory analysis and water retention and density measurements on a limited sample of horizons (35). Different SAWC were computed from the collected data. They differed in the methods i) for estimating the fine earth water retention – national vs local pedotransfer function -, ii) for dealing with the coarse fragments – assumed to contribute or not to the water retention of soils- and iii) for estimating the soil volumes – variable thicknesses and considerations of rooting. The results showed that the SAWC that explained the best the variations of tree fertilities over the study area (21% of the variance) was obtained by fine earth water retention estimated from a local pedotransfert function, by considering the water retention of the coarse fraction and by exploring the largest volumes (thicknesses of 200 cm, 300 cm and equal to the depth to bedrock) without explicit consideration of the rooting observations. The ranking of SAWC component impact on SAWC values was i) soil volume, ii) coarse fraction water retention and iii) fine earth retention. Those results revealed that improvements in estimating coarse fraction water retention and soil volumes, and, to a lesser extent, in estimating fine-earth water retention by forest soil adapted pedotransfer function, would greatly benefit to the application of the SAWC indicator to forest soils.

Keywords: soil available water capacity, forest soils, Douglas-fir, rock fragment water retention, pédotransfert function.

1. Introduction

Soil available water capacity (SAWC) is a well-known concept that have been used for a long time for expressing the capacity of soils to store water for plants (Veihmayer and Hendrickson, 1927). It has been demonstrated that SAWC is one of the most important soil factors for plant growth, influencing photosynthesis rate, carbon allocation, and nutrient cycling (Lebourgeois et al., 2005; Breda et al., 2006). It is therefore a first order parameter that is used in land evaluations and recently in soil ecosystem service assessment (Dominati et al. 2014). For now, in the literature, SAWC is expressed as follows (equation 1) (Cousin et al., 2003):

$$SAWC = \sum_{Hi} Thickness_{(Hi)} \times \left[\left(W_{(FC)-} W_{(Wp)}\right) \times D\right]_{(Hi)} \times \frac{100 - CF}{CF}_{(Hi)} \qquad (1)$$

Where Hi is the horizon i of the soil profile, $Thickness_{(Hi)}$is the horizon thickness in centimeters, $W_{(FC)}$ is the gravimetric water content at the field capacity for fine earth of the horizon, $W_{(Wp)}$is the gravimetric water content at the wilting point for fine earth of the horizon, D is the bulk density of the fine earth of the horizon, CF is volume of the coarse fraction of the horizon in percentage. This equation can be divided in three components: i) the fine earth water retention properties that is usually estimated by pedotranfert functions (PTF) (Wösten et al., 2001; Bruand et al., 2003; Almajou et al., 2008) ii) the coarse fraction volume, that is usually excluded from the equation considering that coarse fragments do not contain available water and iii) the thickness of the material that weights the AWC of each horizon through the soil profile.

SAWC concept has been created for crop field soils, but is also largely applied to forest soils (Curt et al., 2001; Chen et al., 2002; Seynave et al., 2005; Piedallu et al., 2011). SAWC is commonly used in combination with climatic and topographic data in order to predict site fertility of a forest stand (Chen et al., 2002; Seynave et al., 2005). It is also used for soil water balance calculation (Granier et al., 1999) in order to study the forest-stand response to drought that is becoming a crucial issue in context of climate changes (Breda et al., 2006; Sergent et al., 2012; Littke et al., 2018).

However, applying SAWC indicator to forest soils carries some difficulties related with the specificities of forest soil and forest context. Firstly, trees are powerful plants whose roots may colonize a greater soil thickness than cultivated plant. Many studies showed that colonization by roots could go far beyond the soil, reaching the saprolite zone in which this colonization can be very irregular (Curt et al., 1998; Graham et al., 2010; Brantley et al., 2017). This makes not straightforward to define in equation 1 an appropriate value of thickness that account for this heterogeneity. Second, by reaching the saprolite zone, forest soils often show high coarse fraction volumes. It has been demonstrated that coarse fragment can store water which could be available for plant (Flint and Childs, 1984; Tetegan et al. 2011; Parajuli et al., 2017). When the proportion of coarse fragment becomes important, this could play a major role in SAWC. Hence, equation 1 should be modified for taking into account the AWC of the coarse fraction ($AWC_{(CF)}$). Lastly, the determination of the fine earth AWC ($AWC_{(FE)}$) has been by far much more investigated than the two previously evoked components. To cope with metrologic difficulties in measuring gravimetric water content at field capacity ($W_{(FC)}$) and at wilting point ($W_{(WP)}$) there is a wide use of pedotransfer functions (PTF) (Jamagne et al., 1977; Wösten et al., 2001; Almajou et al., 2008). However, most of these PTF have been developed from agricultural soil measurements and to our knowledge, no specific PTF for forest soils exists (Vincke and Delvaux, 2005; Piedallu et al., 2011). Piedallu et al (2018) promoted the use of Almajou 2008' PTF which is derived from agricultural soils. The applicability of PTF to forest soil remains unknown.

In this paper, we apply the concept of SAWC for characterizing the potential of growth of Douglas-fir in the Haut Languedoc Regional Nature Parc (Southern France). Different modalities for calculating the SAWC components are applied from a dataset of 100 deep soil pits. The resulting SAWCs are evaluated with regard to their correlation with an indicator of tree growth.

2. **The study area and data**

2.1. General description

The Haut Languedoc Regional Nature Park is a 314 000 hectares area located in the south of France. This area is covered at 66% by forest, making wood production a crucial issue for the region. The studied area lays through the confluence zone of three contrasted climates. At the east, Mediterranean climate present an annual rainfall of 650mm, concentrated during autumn and spring seasons, and is characterized by a high summer water deficit (-300mm). In the west, oceanic climate is more humid (1650mm annual rainfall) with a more uniform rainfall regime and a lower summer water deficit (-100mm). Finally, in the north, a semi-mountain climate shows wetter and colder average conditions. Geology and topography are also very heterogeneous. The south-west of the study area, called black mountain, is composed on granitic and gneissic mountains reaching 1200 meters high. The center of the area is composed on granitic and gneissic plateau ranging between 800 and 1100 meters high, surrounded by schist and calcschist hills in the north west and schist and calcareous materials in the south east. Such peripheric regions show lower altitude but very rugged terrain with deep valleys and narrows crests. Such variability implies very heterogeneous forest soil type distribution and thus, a large range of SAWC.

2.2. Plot sampling

A 100 plots sampling design was set up in order to exhaustively represent forest soils of the studied area. The sampling design was performed on Douglas-Fir (*Pseudotsuga menziesii*) plantations because this species is of high economic interest and is therefore widely represented across the different climates and parent materials of the study area, which ensures to get a large range of soil conditions. Sampling strategy was based on the combination of climatic, geologic, and topographic classifications. Three sub-zones were distinguished: the central mountain zone (mountain climate), the western zone (oceanic climate) and the eastern zone (Mediterranean climate). Topography classification included four topographic positions: plateau, top slope, mid slope and lower slope combined with three exposition modalities (north, south and other). In the central zone, classification was based on topographic conditions combined with an altitude threshold (800 meters). For the western and eastern zones, topographic classification was combined with geologic classification: schist and granites rocks in the western zone, schist and calcareous rocks in the eastern zone. Sampling strategy also took into account practical conditions such as accessibility for a 25 tons shovel, optimization of the shovel transport, and forest owner agreement.

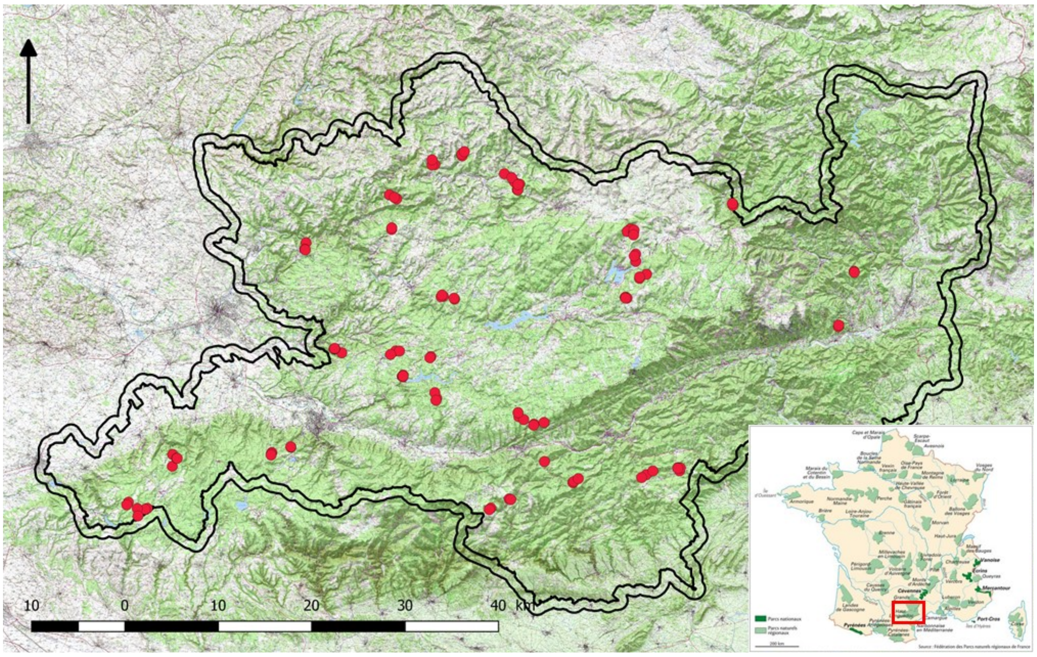

Figure 1: spatial distribution of the sampling plots in the studied area

2.3. Soil observations

For each plot, a soil pit was dug using a 25 tons shovel. The soil pit was positioned at a two meters distance from the tree localised at the centre of the trees spiral composing the plot.

Soil material was excavated until the inscrutable bedrock was reached. When bedrock was too deep underground, the soil pit limit was 4.5 meters depth, corresponding on the maximum accessible depth for the shovel mechanical arm. Soil profiles were visually described following the French protocol of soil description (Infosol, 2018), including the measurement of the soil horizons thickness. Sometimes the soil horizons presented a complex geometry i.e. non-horizontal horizon limits, discontinuous, or enclosed horizons, into the saprolite zone. Non-horizontal horizon limits were registered using the DONSOL protocol. Discontinuous and enclosed horizons were considered as component of a complex horizons, which required to modify the description protocol. Furthermore, graphical representations of each profiles were performed to memorize the observed horizon complexity.

A particular attention was paid for characterizing coarse fraction, both quantitatively and qualitatively. The classical estimation of the amount of coarse fragment from a visual interpretation of the profile was replaced by a more precise technique that estimated separately the gravel fraction (between 2mm and 2cm diameter) and the pebbles fraction (more than 2 cm). The latter was determined in the field by a 2 cm sieving and weighing. The determined fine earth and pebble densities were used to convert mass fraction into volumetric fractions. The gravel fraction was determined in the laboratory from the 2cm-sieved samples obtained from the previously evoked operation. The total coarse fraction was obtained by adding the two previously determined fractions.

A total of 80 rock fragments were sampled for density and water retention measurement. The sampling considered eight rock fragment types that corresponded to the mainly represented lithologic classes of the studied area: mica-schist, black schist, shale, pelitic sandstone, banded sandstone, dolomite, limestone, granite and gneiss. Ten samples of each lithologic class were collected. The rock samples consisted of flat-shaped pebbles with a size varying between 3cm and 6cm for the longer diameter. The samples were gently brushed prior measurement, in order to remove their fine earth coatings.

Considering the fine earth, 200 grams samples were collected from each soil horizon in order to measure five class particle size distribution and organic matter content. In addition, undisturbed clods were sampled from 35 horizons (A and S horizons), for water retention measurements. The sampled clods were chosen in order to exhaustively represent the soil types of the studied area. The undisturbed clods were gently fragmented by hand in order to form 5 cm diameter clods. The samples were kept in plastic boxes and stored at 4°C until analyses.

2.4. Water retention and dry bulk density measurements

Rock fragments and clods gravimetric water content was determined at field capacity (-330 hPa) ($W_{(FC)}$) and at wilting point (-15000 hPa) ($W_{(WP)}$) following a classical protocol (ref). Measurements were performed on a pressure membrane. After saturation by capillarity, samples were placed on a paste of saturated kaolinite to obtain a sufficient hydraulic continuity with the pressure membrane. After one week of equilibrium in pressure cells, the gravimetric water content was measured.

Dry bulk density was estimated using the paraffin method (ref). Samples were dipped into hot paraffin. By cooling, a thin paraffin coating was formed and blocked the sample pores. Paraffin coated-samples were dipped into a water container, and the coated sample volume was estimated by the water displacement. Finally, the paraffin coating was carefully removed from the sample using a cutter. Paraffin residues were weighed and the volume of the coating was calculated. The rock fragment bulk density was calculated by the difference between the coated sample volume and the paraffin volume. The measurement of bulk density, gravimetric water content at field capacity and wilting point were repeated and averaged on 10 different samples for each fine earth horizon, and each rock fragment lithologic class.

Following the measurements, both fine earth and coarse fragment water retention properties were calculated and summed up into an AWC coefficient (AWCcoef) calculated using the following equation 3.

$$AWCcoef = \left(W_{(FC)} - W_{(Wp)}\right) * D * 0.1 \quad (3)$$

Where $W_{(FC)}$ is the gravimetric water content at field capacity in mm, $W_{(WP)}$ is the gravimetric water content at the wilting point in mm and D is the bulk density.

Coarse fraction AWC coefficient ($AWCcoef_{(CF)}$) was calculated for the eight considered lithologic classes. Fine earth AWC coefficient was calculated for the 35 sampled horizons ($AWCcoef_{(FE)}$).

2.5. Root measurements

For each soil profile, the depth of the deepest visible root was measured. At the horizon scale, root density was estimated by counting. For each horizon, three 10*10 cm squares areas were considered. The first square was localized on the highest root density zone of the horizon, the second square on the lowest density zone and the third was localized on the medium root density zone. For each square, visible roots with a diameter less than 2 cm, were counted and classified by health status (healthy, dead).

2.6. Site fertility Index H50

A forest stand plot consisted of a 20 dominant trees spiral. Each diameter at breast height (1.30 m) was measured. The dominant height of the three largest trees was measured using a Vertex laser dendrometer. The age was measured using a Pressler increment borer. Site fertility index was calculated for each stand at the reference age of 50 years ($H_{(50)}$) using the model by Angelier (2006).

3. SAWC calculations

SAWC was determined for each of the 100 soil profiles from the collected data. We present in the following the different modalities that were considered for determining each SAWC components and further the combinations of modalities used to determine different possible SAWC for a given soil profile.

3.1 Fine earth horizon AWC

Fine earth horizon AWC was determined for each horizon by two different methods. The first was the class PTF from Al Majou (2008) that was recently recommended as the best one for application in forest soil (Piedallu et al., 2018). Considering this method, $AWCcoef_{(FE)}$ was attributed to each horizon in function of the textural class measured in the laboratory and the soil horizon type (Al Majou, 2008). The second method used a local continue PTF that was computed from the 35-clods dataset. A linear regression was performed to predict the measured $AWCcoef_{(FE)}$ or its calculation parameters ($W_{(FC)}$, $W_{(WP)}$ and D) by using simple soil properties as explanatory factors (sand, silt, clay and organic matter amount). The best model among all the tested combinations predicted $AWCcoef_{(FE)}$ by the following equation 4.

$$LocalAWCcoef_{(FE)} = [(36{,}4934 + Sand * -0{,}1055) - (15{,}752 + OM * 0{,}7095)] * 0.1 \tag{4}$$

Determination coefficient R^2=0.23; n=35

Where W(FC) is the volumetric water content at field capacity, W(WP) is the volumetric water content at wilting point, Sand is the sand content in % and OM is the organic matter content in %. Considering this method, $LocalAWCcoef_{(FE)}$, was calculated for each horizon.

3.2 Coarse fragment horizon AWC

Two different modalities for dealing with coarse fragment in the calculation of SAWC were considered. The first was the usual one that calculates SAWC without integrating coarse fraction AWC (equation 1). Such approach, comes to assume that the coarse fraction cannot store available water for plant. $AWCcoef_{(CF)}$ is then equal to zero, and only fine earth fraction AWC is taken into account. The results of SAWC calculation that followed this modality were further denoted as $SAWC_{(FE)}$. The second assumes an effective contribution of the coarse fraction to the SAWC. For such method, $AWCcoef_{(CF)}$ was attributed to each horizon depending on the coarse fraction lithology. The results of SAWC calculation that followed this modality were further denoted as $SAWC_{(total)}$.

3.3. Soil profile thicknesses

The previously mentioned equation 1 represents the contribution of soil volume in SAWC by a value of thickness, which implicitly supposes that the horizons are perfectly horizontal. Thus, the horizons presenting a complex geometry must be converted into an "equivalent horizontal" horizon thickness, calculated as follows (equation 5).

$$Equivalent\ horizon\ Thickness = \frac{Vol_{(h)}}{100} \times Thickness_{(prof)} \quad (5)$$

Were soil thickness is expressed in mm; Vol (h) is the complex horizon volume in %; $Thickness_{(prof)}$ is the thickness of the soil profile in mm.

SAWC was computed for different soil volumes. First, the whole soil profile volume was considered. This comes to define the soil thickness (i.e. the sum of horizon thicknesses in equation 1) as the distance from the soil surface to the inscrutable bedrock without consideration of the rooting ($SAWC_{(Bedrock)}$). If the bedrock was too deep, the thickness limit was 4.5 meters. Secondly, soil volume consisted to limit the soil thickness to an arbitrary fixed value that define the maximal rooting depth beyond which the tree is not supposed to extract water. Soil thicknesses of 300 cm, 200 cm, 100 cm and 50 cm were considered ($SAWC_{(300)}$, $SAWC_{(200)}$, $SAWC_{(100)}$, and $SAWC_{(50)}$). By the same, a fixed floor corresponding to the depth of the deepest observed root was also considered ($AWC_{(Max\ root\ depth)}$). Finally, an alternative method for taking into account more precisely the tree root dispersion was considered. Instead of modifying the value of soil thickness, a roots density index was introduced in the AWC calculation of each horizon. This index was based on a classification derived from Baize and Jabiol (1995) presented in table 1. The mean root density used as input for this classification were calculated from the root observations performed across the 100 soil profiles.

Table 1: classification of the root density at the horizon scale

Mean root density (3 squares)	**Minimum root density**	**Medium root density**	**Maximum root density**	**Root density index**
>16 / dm²	-	-	-	**1**
>8 /dm² and <16 / dm²	>1	-	-	**1**
	0	-	-	**0.75**
>0 /dm² and < 8/dm²	0	>1	-	**0.75**
	0	0	>5	**0.5**
	0	0	<5	**0.25**
0 /dm²	0	0	0	**0**

3.4. The different considered SAWC

The different modalities for determining the three components of SAWC were combined to produce 28 estimations of SAWC, i.e. two different fine earth approaches (“Almajou2008” PTF and “local” PTF) x two different coarse fraction approaches ($SAWC_{(Total)}$, $SAWC_{(FE)}$) x seven different soil volumes (Table 2).

Table 2: description of the soil volumes considered for SAWC calculation

Name	Soil volume
$AWC_{(Bedrock)}$	From soil surface to the inscrutable bedrock If Bedrock was too deep, the depth limit was 4.5 meters
$AWC_{(300)}$, $AWC_{(200)}$, $AWC_{(100)}$, $AWC_{(50)}$	from the surface to a fixed floor depth. 300 cm ; 200 cm ; 100 cm ; 50 cm
$AWC_{\text{(Max root depth)}}$	From soil surface to the deepest root observed in the pit
$AWC_{\text{(Root density)}}$	From soil surface to the inscrutable bedrock. AWC weighted by the horizons root density index

4. Results

4.1 Basic soil characteristics: average values and variability across the region

Table 3 presents the statistics of the main soil properties that influence SAWC. With a mean of 254 mm, and exceeding 400 centimeters for some plots, the soil thickness reached frequently the saprolite horizon. The studied soils showed high coarse fragments content (55% at the scale of the soil profile) mainly concentrated in the saprolite horizons. The soil textures were weakly variable across the study area. Most of the profiles were classified as sandy loams, with high sands content resulting from the weathering of granite, gneiss, sandstones and schists. Finally, soil was also characterized by an high organic matter content in the surface horizons (mean = 6.0 %) that remain non negligible in S horizons (mean = 2.7%).

Table 3: soil thickness, rock fragment content, clay content, silt content, sand content and organic matter content for the different soil layers of the data set.

	Thickness (mm)	**%Coarse fraction**	**Clay%**	**Silt%**	**Sand%**	**OM%**

	mean	sd	mean	sd	mean	sd	mean	sd	mean	sd	mean	sd
Profile	**254.0**	**107.0**	**55.5**	**20.0**	**10.3**	**6.8**	**29.3**	**10.6**	**57.3**	**15.7**	**1.1**	**1.0**
Pedolit	**67.1**	**29.0**	**21.0**	**16**	**12.9**	**6.6**	**32.1**	**11.1**	**51.0**	**14.7**	**4.7**	**1.9**
A horizon	*26.2*	*9.0*	*15.0*	*4.0*	*15.7*	*6.3*	*32.7*	*10.3*	*51.6*	*14.7*	*6.0*	*1.8*
S horizon	*36.9*	*21.2*	*27.0*	*22.0*	*11.0*	*7.7*	*33.6*	*13.7*	*55.4*	*18.0*	*2.7*	*1.2*
Saprolit	**185.4**	**101.0**	**70.9**	**22**	**9.2**	**7.4**	**27.9**	**11.2**	**60.1**	**17.4**	**0.4**	**0.3**

4.2 Water retention of fine earth

Considering the 35 fine-earth clods used for the hydric property measurements, the *AWCcoef*$_{(FE)}$ calculated from the measured parameters ($W_{(FC)}$, $W_{(WP)}$ and *D*) and the *AWCcoef*$_{(FE)}$ estimated by Almajou PTF showed significant correlations but low coefficient of determination (r^2=0.14). Both *AWCcoef*$_{(FE)}$ varied into similar ranges, and did not showed significant differences. The *AWCcoef*$_{(FE)}$ estimated from the local PTF was significantly and positively correlated with the *AWCcoef*$_{(FE)}$ calculated from the measured hydric properties (r^2=0.23) (Figure 2).

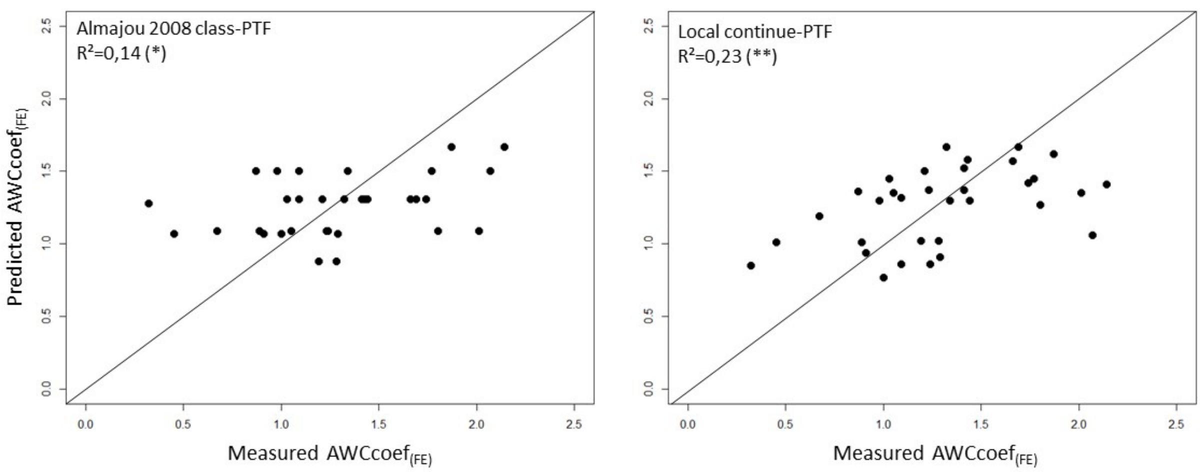

Figure 2: determination coefficients (R^2) between AWCcoef$_{(FE)}$ measured and predicted using Almajou PTF (2008) and using the "local" PTF. N=35

$AWCcoef_{(FE)}$ were estimated for each horizon of the 100 soils profiles using both local PTF and Almajou PTF. For A horizons, the $AWCcoef_{(FE)}$ estimated by the local PTF were significantly higher than the $AWCcoef_{(FE)}$ estimated by Almajou PTF. The deeper horizons showed opposite results: the $AWCcoef_{(FE)}$ estimated by local PTF showed significant lower values than those estimated with Almajou PTF.

4.3 Water retention of the coarse fragments

Results of the rock fragments hydric properties measurement showed that the samples contained available water for the trees (table 4). The $AWCcoef_{(CF)}$ varied with the lithology class of the rock fragment, with a minimum coefficient for the black schist and a maximum coefficient for the shale. Granit, gneiss and mica-schist fragments which are the main lithologic class of the studied area showed respectively $AWCcoef_{(CF)}$ of 0.58, 0.46 and 0.67.

Table 4: Bulck density (D), gravimetric water content at field capacity ($W_{(FC)}$) and Wilting point (($W_{(WP)}$), and the calculated available water capacity coefficient for coarse fraction ($AWCcoef_{(CF)}$) for each lithologic class. N=10. sd = standard deviation

Lithologic class	Geologic period	D	*sd*	$W_{(FC)}$ %	*sd*	$W_{(WP)}$ %	*sd*	$AWCcoef_{(CF)}$
Mica-schist	Cambro-Ordovician	2,09	*0,13*	5,55	*0,76*	2,33	*0,47*	**0,67**
Pelitic sandstone	Lower Cambrian	2,19	*0,11*	6,03	*2,74*	2,74	*1,36*	**0,72**
Banded sandstone	Lower Cambrian	1,87	*0,04*	10,9	*0,46*	9,3	*0,28*	**0,30**
Black schist	Lower Cambrian	2,19	*0,08*	4,44	*0,46*	3,96	*0,35*	**0,11**
Shale	Lower Cambrian	1,74	*0,11*	11,58	*3,51*	4,63	*0,86*	**1,21**
Dolomite	Lower Cambrian	2,13	*0,07*	3,86	*1,27*	2,82	*0,96*	**0,22**
Granite	Westphalian	2,27	*0,09*	4,26	*0,59*	1,7	*0,54*	**0,58**
Gneiss	Cambrian	1,93	*0,2*	5,78	*2,01*	3,39	*0,78*	**0,46**

4.4 Relative contribution of modalities to the variations of SAWC calculation

Table 5 shows the SAWC values calculated for the seven mentioned soil volumes, and following the different approaches for coarse fraction and fine earth fraction. Table 6 shows the results of the student tests assessing the effect of the coarse fraction and fine earth fraction approaches.

$AWC_{(Bedrock)}$ showed the highest SAWC values with a mean of 227.6mm and a maximum value reaching 547.0mm (Table 5). SAWC decreased gradually while decreasing the fixed floor depth. $AWC_{(Max\ root\ depth)}$ showed always lower values than $AWC_{(Bedrock)}$, meaning that, in average, the roots maximum depth did not reached the bedrock depth. $AWC_{(Root\ density)}$ showed mean values 34 % to 45 % lower than $AWC_{(Bedrock)}$. SAWC calculated by integrating the coarse fraction AWC ($AWC_{(Total)}$) showed significant different values than AWC calculated by excluding the coarse fraction AWC ($AWC_{(FE)}$), whatever the considered soil volume (Table 6). $AWC_{(Total)}$ was always higher than $AWC_{(FE)}$ (Table 5). Considering $AWC_{(FE)}$, significant differences were only observed for the fixed floors beyond 200 cm depth. Considering the soil volume until the bedrock depth, SAWC values did not differ significantly regarding the PTF used to calculate the $AWCcoef_{(FE)}$. Result was the same considering the rooted volume, or the volume until 300- and 200-centimeters depth. However, result differed for the surface material AWC: significant differences were found between AWC values calculated from the local PTF, and AWC values calculated from the Almajou 2008 PTF (Table 6).

Table 5: maximum, minimum and mean values for all the SAWC calculation. N=100

Soil volume	**$AWCcoef_{(FE)}$**	**$AWCcoef_{(CF)}$**	**Mean (mm)**	**Standard deviation**	**Minimum (mm)**	**Maximum (mm)**
$AWC_{(Bedrock)}$	Local	$AWC_{(Total)}$	227.6	117.2	46.4	547.0

		$AWC_{(FE)}$	139.4	86.4	25.6	481.9
	Almajou	$AWC_{(Total)}$	216.0	104.3	59.5	479.2
		$AWC_{(FE)}$	131.4	69.7	29.1	376.1
$AWC_{(Max\ root\ depth)}$	Local	$AWC_{(Total)}$	192.3	93.4	35.2	489.1
		$AWC_{(FE)}$	117.6	55.2	24.9	365.2
	Almajou	$AWC_{(Total)}$	180.8	90.1	51.2	411.7
		$AWC_{(FE)}$	109.8	45.9	28.5	303.8
$AWC_{(Root\ density)}$	Local	$AWC_{(Total)}$	124.4	58.0	34.9	326.3
		$AWC_{(FE)}$	85.6	37.8	25.7	201.7
	Almajou	$AWC_{(Total)}$	125.9	56.1	31.5	312.0
		$AWC_{(FE)}$	86.9	38.5	21.3	208.6
$AWC_{(300)}$	Local	$AWC_{(Total)}$	208.3	98.4	46.4	497.7
		$AWC_{(FE)}$	132.6	77.5	25.6	439.8
	Almajou	$AWC_{(Total)}$	198.0	87.1	59.5	465.9
		$AWC_{(FE)}$	122.3	63.1	29.1	344.7
$AWC_{(200)}$	Local	$AWC_{(Total)}$	166.4	60.2	46.4	338.0
		$AWC_{(FE)}$	115.5	58.8	25.6	313.6
	Almajou	$AWC_{(Total)}$	159.4	51.7	59.5	298.0
		$AWC_{(FE)}$	108.4	48.5	29.1	250.4
$AWC_{(100)}$	Local	$AWC_{(Total)}$	97.4	23.4	42.3	171.9
		$AWC_{(FE)}$	79.1	30.1	24.9	171.6
	Almajou	$AWC_{(Total)}$	96.9	18.0	41.9	141.4
		$AWC_{(FE)}$	78.5	25.2	25.5	141.1

$AWC_{(50)}$	Local	$AWC_{(Total)}$	51.7	10.7	26.1	82.3
		$AWC_{(FE)}$	46.1	13.3	18.7	81.9
	Almajou	$AWC_{(Total)}$	55.9	8.0	26.3	71.4
		$AWC_{(FE)}$	50.3	11.4	18.9	71.1

Table 6: effect of the PTF and coarse fraction parameters on SAWC calculation for the 7 soil volumes, using student test. N=100. NS= non-significant difference; significant difference at the 0.05 (*) ; 0.01 (**) and 0.001 (***) thresholds.

	PTF effect	Coarse fraction effect
	Almajou Vs local PTF	$AWC_{(FE)}$ Vs $AWC_{(Total)}$
$AWC_{(Bedrock)}$	NS	***
$AWC_{(Max\ root\ depth)}$	NS	***
$AWC_{(Root\ density)}$	NS	**
$AWC_{(300)}$	NS	***
$AWC_{(200)}$	NS	***
$AWC_{(100)}$	*	***
$AWC_{(50)}$	**	**

4.5 Relation with tree growth

Site fertility index, measured by H_{50} showed a mean of 35.4 meters high and a standard deviation of 3.6. The most fertile plot reached a H_{50} of 44.6 m while the lowest fertility index was 26.8 m.

Table 7: Spearman's correlation coefficients between the fertility index (H_{50}) and SAWC calculated for the 7 soil volumes, including $AWC_{(CF)}$ ($AWC_{(Total)}$) or excluding it ($AWC_{(FE)}$), and using the local PTF or Almajou PTF for $AWCcoef_{(FE)}$ estimation. N=100. NS= non-significant difference ; significant difference at the 0.05 (*) ; 0.01 (**) and 0.001 (***) thresholds.

		$AWCcoef_{(FE)}$			
SAWC	**$AWCcoef_{(CF)}$**	**Almajou PTF**		**Local PTF**	
$AWC_{(Bedrock)}$	$AWC_{(Total)}$	0.47	***	0.48	***
	$AWC_{(FE)}$	0.40	***	0.42	***
$AWC_{(Max\ root\ depth)}$	$AWC_{(Total)}$	0.32	**	0.35	**
	$AWC_{(FE)}$	0.30	**	0.31	**
$AWC_{(Root\ density)}$	$AWC_{(Total)}$	0.29	**	0.31	**
	$AWC_{(FE)}$	0.25	*	0.26	*
$AWC_{(300)}$	$AWC_{(Total)}$	0.44	***	0.48	***
	$AWC_{(FE)}$	0.37	**	0.40	***
$AWC_{(200)}$	$AWC_{(Total)}$	0.42	***	0.45	***
	$AWC_{(FE)}$	0.34	**	0.37	**
$AWC_{(100)}$	$AWC_{(Total)}$	0.35	**	0.37	**
	$AWC_{(FE)}$	0.28	*	0.29	*
$AWC_{(50)}$	$AWC_{(Total)}$	0.26	*	0.28	*
	$AWC_{(FE)}$	0.18	NS	0.24	*

SAWC correlated significantly and positively with H_{50} whatever the considered soil volume except for $AWC_{(50)}$. The best correlation coefficients were found for the greatest volumes of soil without including the rooting effect ($AWC_{(Bedrock)}$, $AWC_{(300)}$ and $AWC_{(200)}$). Whatever the considered material, SAWC showed better correlation coefficient with H_{50} when it included the $AWC_{(CF)}$. The effect of the chosen PTF for estimating the $AWC_{(FE)}$ did not alter the relationship between SAWC and H_{50}: correlation coefficients were not significantly different.

5. Discussion

5.1 Fine earth water retention

The forest soils considered for the present study showed relative homogeneous sandy texture, high organic matter content. Such soil properties induced specific water retention behavior for the fine earth that were found to be very hardly predicted by using Almajou PTF. Indeed, while the Almajou PTF predicted homogeneous $AWCcoef_{(FE)}$, the coefficients based on the measured values showed higher variability, especially for the surface horizons.

Texture, as an only factor, might not be able to predict water retention for the studied soils. It seems that organic matter content may play an important role. Indeed, such relationship was partly found by using the continue local PTF. However, even if the relationship was statistically significant, it only allowed to predict 23 % of the measured water retention variability. This lack of performance can be explained by the low number of samples used in this study (35) combined with a low range of water retention properties ($W_{(FC)}$, $W_{(WP)}$) in comparison to other studies (ref).

Anyway, the fine earth retention seems not to impact less the variation of SAWC than other factors. As an explanation, the volume of fine earth has a very homogeneous soil texture. Furthermore, it is smaller than usually measured due to the richness in coarse fragments, and the increase of coarse fragment with depth result in a decrease of fine earth AWC impact. As a conclusion, the increase of variations of other AWC components than fine earth may explain this weak importance. However, it should be tried in more texture contrasted pedological context. It is also worth noting that recommended PTF failed to represent the fine earth retention variability and that the local PTF stress the negative impact of organic matter on the wilting point, which, to our knowledge have never been encountered in studies dealing with agricultural soils. This re-enforce the need of specific PTF for forest soils.

5.2 Retention of coarse fragment

The water retention capacity of coarse fragment based on measurements was found important to take into account for explaining tree growth. The correlation coefficients raised significantly whatever the considered soil volume with however greater differences when deeper layers were considered. It is explained by the importance of coarse fragment, especially in the saprolite zone, but also to the substantial water retention of some of the pebbles.

Indeed, we measured $AWCcoef_{(CF)}$ varying between 0.11 and 1.21 depending on the rock fragment lithology. This is consistent with previous studies (Tetegan et al., 2011; Parajuli et al., 2017). Parajuli et al., 2017 showed that the water retention capacity of sandstones fragment was linked to the sample porosity. Tetegan et al. studied the water retention capacities of different types of sedimentary rocks. They found that the $AWC_{(CF)}$ depends on the rock fragment bulk density, with the higher $AWCcoef_{(CF)}$ for bulk density varying between 1.5 and 1.8. The results of the present study for $AWCcoef_{(CF)}$ values were very similar, even if the lithologic nature of the studied samples was very different. Considering the studied soils, the $AWC_{(CF)}$ represented 39 % of the $AWC_{(Total)}$ for the $AWC_{(Bedrock)}$ and 31 % for the $AWC_{(200)}$. We recommend that water retention of coarse fragment could be also accounted for. The variability shown in this study suggest that PTF should also be built for coarse fraction, and especially for the weathered rock fragment showing a low bulk density and high porosity. Finally, this result also underlined the crucial importance of a precise assessment of the coarse fraction volume within the soil profile. A 2cm- sieving and weighing performed in the field appeared to be a progress from classical visual estimations from the profile wall.

5.3 Soil Volume

Soil volume seems to be the main driver of SAWC in our study area. We showed that for Douglas-fir fertility index, the best correlation coefficients were obtained with SAWC calculated on the thickest and deepest materials: $AWC_{(Bedrock)}$, $AWC_{(300)}$ and $AWC_{(200)}$. Anyway, with correlation coefficients quite similar than $AWC_{(Bedrock)}$, $AWC_{(200)}$ seemed to be deep and thick enough for accounting for the soil impact on the tree growth. This might mean that the critical AWC layer for tree fertility was not the global and potentially rooted saprolite zone, but a thinner volume of material that concentrated the higher root density (Brantley et al., 2017). In this way, the SAWCs taking into account direct observations of rooting depths (AWC $_{(Max\ root\ depth)}$, AWC $_{(Root\ density)}$) would have been theoretically the best methods for assessing SAWC. Indeed, root distribution is like a map of were water is most likely to be present during the growing season (Brantley et al., 2017). Curt et al., 1998 proposed a typology for the root-system architecture of Douglas-fir that was strongly correlated with Douglas-fir fertility index (H_{25}). However, it was not the case for the present study. The correlation coefficients with H_{50} were lower for the SAWC weighted on the root density than for SAWC based on fixed floor depth. This can be explained by the difficulty in observing functional roots that are very thin (diameter <1mm) and by the omission of mycorrhizal effect.

Finally, the lower correlation coefficients were found for the surface material $AWC_{(100)}$ and $AWC_{(50)}$. Such material seemed to be not thick and deep enough to precisely characterize the SAWC potential for a given site. This result questions the common field method for SAWC assessment that used manual auger to probe the soil with a very limited depth.

5.4 AWC – tree growth relation

The SAWC-tree growth relation was found significative with SAWC explaining at best 23% of the H_{50} variability. Many studies explored the relationships between tree growth and SAWC. Piedallu et al. (2011) showed that SAWC calculated by using manual auger, Almajou PTF for estimating $AWC_{(FE)}$, and without including the coarse fraction AWC could explained at most 12 % of the fertility index of Fagus sylvatica, Picea Abies and Quercus Petraea. Curt et al., (2001) showed that SAWC explained 29 % of Douglas-fir growth in the Limousin (French Massif Central). For this study, SAWC was calculated on 1-meter depth pit using by the “texture method” (Baize & Jabiol, 1995), and Douglas-fir growth was estimated at the reference age of 25 years. This stronger relationship for Curt et al. (2001) can be explained by a more homogeneous climate and geology of the studied area than ours. Indeed, for the Haut-Languedoc area, the climatic confluence situation and the geological heterogeneity induced very complex interactions between the Douglas-fir growth factors. Climate variables such as an early vegetative season water deficit (Sergent et al., 2012) and other factors such as chemical fertility, former land use (Curt et al., 2001), or genetic origin of Douglas-fir trees (Bansal et al., 2015) may also play an important role. SAWC appeared as a complementary factor, but can be more useful when the first-order factors such as climate remain weakly variable.

6. Conclusion

SAWC concept which was created for agricultural soils requires specific adaptations when it is estimated for forest soils. The present study pointed three possible improvements for forest SAWC assessment: 1) the development of specific PTF for forest soils, integrating texture and organic matter content as explanatory factors for fine earth water retention properties, 2) the integration of the coarse fraction AWC for SAWC calculation and thus, the development of rock fragment PTF, and 3) the consideration of a 200cm deep soil volume for SAWC assessment. This last point appears to be the most difficult to practically take into account in usual field sampling devices, because the digging of such a soil volume is expansive. Thus, the modelling of the total soil thickness by using available surface and subsurface indicators could be a crucial issue for forest soil AWC assessment.

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