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Variation of the water retention properties of soils: Validity of class-pedotransfer functions

Variation des propriétés de rétention en eau des sols : Validité des classes de pédotransfert

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Abstract

Water retention properties of soils vary according to soil characteristics and understanding of their variation remains controversial. Numerous pedotransfer functions (ptfs) that enable prediction of the water retention properties of soils were developed but their validity was poorly discussed. In this study we compare the performance of textural and texturo-structural class-ptfs with more sophisticated class- and continuous-ptfs developed using the same set of soils. We showed that the former led to prediction performance that are better or similar to those recorded with the more sophisticated class- and continuous-ptfs studied. Thus, textural and texturo-structural class-ptfs that are quite easy to establish are potentially worthwhile tools for predicting the water retention properties of soils, particularly at scales for which semi-quantitative or qualitative basic soil characteristic such as the texture are the only characteristic available. More generally, our results pointed out that the discussion of ptfs performance should refer to those recorded with easy to establish ptfs, thus enabling to quantify how much prediction bias and precision can be gained when increasing the complexity of ptfs and consequently the number and quality of predictors required.

Keywords: Texture, Bulk density, Horizon, Structure, Prediction bias, Prediction precision

Résumé

Les propriétés de rétention en eau des sols varient en fonction de leur composition et elles sont encore largement discutées. De nombreuses fonctions de pédotransferts (fpt) permettant de les prédire ont été développées mais leur validité n'a été que rarement discutée. Dans cette étude, nous comparons les performances de classes de fpt texturales et texturo-structurales développées en utilisant un même jeu de données. Nous montrons que les classes de fpt conduisent à des performances de prédiction qui sont meilleures ou similaires à celles enregistrées avec les fpt plus sophistiquées étudiées par ailleurs dans cette étude. Ainsi, les classes de fpt texturales et texturo-structurales qu'il est aisé d'établir sont potentiellement des outils utiles pour la prédiction des propriétés de rétention en eau des sols, en particulier aux échelles auxquelles seules des données semi-quantitatives ou qualitatives comme la texture sont disponibles. Plus généralement, nos résultats mettent en évidence que les performances des fpt devraient être discutées en prenant comme référence celles enregistrées avec des fpt faciles à établir comme les classes de fpt texturales. En procédant ainsi, il est alors possible d'apprécier le gain de performance en terme de biais et de précision quand on complexifie les fpt et que l'on accroît le nombre et qualité des caractéristiques de sols requises.

Mots-clés : Texture, Densité apparente, Horizon, Structure, Biais de prédiction, Précision

Introduction

Understanding of soil water retention properties of soil remains a major issue in soil science. Because of the growing demand for soil hydraulic properties, a common solution has been to use pedotransfer functions (ptfs) that relate basic soil properties that are considered as easily accessible to the less often measured soil properties such as hydraulic properties [1]. A huge number of ptfs was developed over the last three decades and we are facing today to the continuous development of ptfs of increasing complexity with very little or no information about the potential increase in the prediction quality. There is some information available about the performance of continuous-ptfs [11, 17], very little about the performance of class-ptfs [14,17] and less again about the compared performance of these two types of ptfs [15]. The aim of this study is to show that variation of water retention properties can be predicted by using stratification based on information about particle size distribution and structure. We show also that the quality of the prediction is similar or better than with much more sophisticated ptfs despite what is usually admitted.

Materials and methods

The ptfs developed in the literature

Most ptfs published in the literature are continuous-pedotransfer functions (continuous-ptfs), i.e. mathematical continuous functions between the water content at discrete values of potential or the parameters of a unique model of water retention curve and the basic soil properties (mostly particle size distribution, organic carbon content and bulk density) [12, 17]. Besides these continuous-ptfs that enable continuously the prediction of water content at particular water potentials [13] or estimation of the parameters of models of the water retention curve [5, 11, 17], there are class pedotransfer functions (class-ptfs) that received little attention because their accuracy is considered as limited [15]. The existing class-ptfs provide often average water contents at particular water potentials or one average water retention curve for every texture class [2, 10]. Due to the range in particle size distribution, clay mineralogy, organic matter content and structural development within each texture class, water retention properties for individual soils were considered as varying considerably [16]. Despite their possible inaccuracies, class-ptfs enable the prediction based on successive stratification using soil characteristics. Moreover, class-ptfs are easy to use because they require little soil information and are well adapted to the prediction of water retention properties over large areas [9, 15, 16]. There is some information available about the performance of continuous-ptfs [11, 17], very little about the performance of class-ptfs [14, 17] and less again about the compared performance of these two types of ptfs [15].

The soils studied

Class- and continuous-ptfs were developed using a set of 320 horizons comprising 90 topsoils (from 0 to 30 cm depth) and 230 subsoil horizons (>30 cm depth) collected in Cambisols, Luvisols, Planosols, Albeluvisols, Podzols and Fluvisols [8] located mainly in the Paris basin and secondarily in the western coastal marshlands and Pyrenean piedmont plain. A set of 107 horizons comprising 39 topsoil and 68 subsoil horizons was constituted in order to test the ptfs established. These horizons were collected in Cambisols, Luvisols and Fluvisols [8] located in the South of the Paris basin. Basic characteristics and water retention properties of the horizons were determined as earlier described by Bruand and Tessier [3] (Figure 1, Table 1). Their bulk density (D_b) was measured by using cylinders 1000 cm^3 in volume when the soil was near to field capacity.

Analysis of the PTFs performance

In order to discuss the global validity of the ptfs, most studies used the root mean square error (*RMSE*) that is also called root mean squared deviation or root mean square residual [17]. Because the *RMSE* varies according to both the prediction bias and precision, we computed the mean error of prediction (*MEP*) that enables discussion of the prediction bias alone on one hand and the standard deviation of prediction (*SDP*) that enables discussion of the prediction precision alone on the other hand. We computed *MEP* and *SDP* for the whole water potentials as follows:

$$MEP = \frac{1}{l^{'} \cdot l} \sum_{j=1}^{l'} \sum_{i=1}^{l} (\theta_{p,j,i} - \theta_{m,j,i})$$

$$SDP = \left\{ \frac{1}{l^{'} \cdot l} \sum_{j=1}^{l'} \sum_{i=1}^{l} \left[(\theta_{p,j,i} - \theta_{m,j,i}) - MEP \right]^2 \right\}^{1/2}$$

where $\theta_{p,j,i}$ is the predicted water content at potential *i* for the horizon *j*, $\theta_{m,i,j}$ is the measured water content at potential *i* for the horizon *j*, and *l* is the number of water potentials for each horizon (l=7 in this study) and *l'* is the number of horizons ($l' \leq 107$ in this study). The *MEP* corresponds to the bias and indicates whether the ptfs overestimated (positive) or underestimated (negative) the water content, whereas *SDP* measures the precision of the prediction.

In order to discuss the validity of the ptfs at the different water potentials we computed also the mean error of prediction (*MEP'*) and the standard deviation (*SDP'*) of prediction at every water potential as follows:

$$MEP^{'} = \frac{1}{l^{'}}\sum_{j=1}^{l'}\left(\theta_{p,j} - \theta_{m,j}\right)$$

$$SDP^{'} = \left\{\frac{1}{l^{'}}\sum_{j=1}^{l'}\left[\left(\theta_{p,j} - \theta_{m,j}\right) - MEP^{'}\right]^{2}\right\}^{1/2}.$$

Results and discussion

The class- and continuous-ptfs developed

The class-ptfs developed in this Note were established according to the texture (textural class-ptfs) in the CEC triangle [4] and then according to both that texture and D_b (texturo-structural class-ptfs). The resulting class-ptfs corresponded to the average water content at 7 water potentials that was computed within every class of texture (textural class-ptfs) (Table 2) and every class combining both texture and D_b (texturo-structural class-ptfs) (Table 3). More complex class-ptfs were established by fitting the van Genuchten's model [6] on the arithmetic mean value of θ at the different values of water potential using the RETC code [7] for every class of texture (VG texture class-ptfs) according to the CEC triangle [4] and the type of horizon (topsoil and subsoil) (Table 4).

Continuous-ptfs were also developed. They correspond to multiple regression equations as follows:

$$\theta = a + (b\times\%Cl) + (c\times\%Si) + (d\times\%OC) + (e\times D_b)$$

with θ, the volumetric water content at a given water content, a, b, c and e the regression coefficients, $\%Cl$ and $\%Si$, respectively the clay and silt content, $\%OC$, the organic carbon content and D_b, the bulk density (Table 5). Other continuous-ptfs were developed as earlier done by Wösten *et al.* [16] for the parameters of the van Genuchten's model using multiple regression equations (VG continuous-ptfs) (Table 6). For every horizon, the parameters of the van Genuchten's model were computed using the RETC code [7].

Validity of the class-ptfs

The textural class-ptfs underestimated very slightly the water retained (MEP = –0.003 cm^3 cm^{-3}) when they are applied to the test dataset without any other stratification than according to the texture. There was no decrease in the prediction bias with the texturo-structural class-ptfs (MEP = –0.004 cm^3 cm^{-3}) but the bias was already very small with the textural class-ptfs studied. However the precision was slightly better with the texturo-structural class-ptfs (SDP = 0.043 cm^3 cm^{-3}) than with the textural class-ptfs (SDP = 0.045 cm^3 cm^{-3}) (Figure 2a and b). Compared to the textural class-ptfs, the VG textural class-ptfs showed similar performance. The bias was very small (MEP = 0.002 cm^3 cm^{-3}) and the precision poor (SDP = 0.045 cm^3 cm^{-3}) as recorded for the textural class-ptfs (Figure 2c). The comparison of the class-ptfs performance at every value of water potential showed small bias ($-0.008 \leq MEP' \leq 0.007$ cm^3 cm^{-3}) except for $\theta_{4.2}$ for the textural and texturo-structural class-ptfs (MEP' = –0.020 and –0.019 cm^3 cm^{-3}) and for $\theta_{1.0}$ for the VG Class-ptfs (MEP' = 0.014

$cm^3\ cm^{-3}$) for which it was greater (Table 7). This comparison showed also poor precision for the three class-ptfs studied whatever the water potential ($0.040 \leq SDP' \leq 0.047\ cm^3\ cm^{-3}$).

Validity of the continuous-ptfs

When applied to the test data set, the continuous-ptfs leads to very small bias ($MEP = –0.003\ cm^3\ cm^{-3}$) and showed poor precision ($SDP = 0.039\ cm^3\ cm^{-3}$). Results showed a greater bias with the VG continuous-ptfs ($MEP = –0.008\ cm^3\ cm^{-3}$) and similar poor precision ($SDP = 0.039\ cm^3\ cm^{-3}$) than with the continuous-ptfs (Figure 2d and e). The comparison of the continuous-ptfs performance at every value of water potential showed small bias for the continuous-ptfs ($–0.006 \leq MEP' \leq 0.005\ cm^3\ cm^{-3}$) except for $\theta_{4.2}$ ($MEP' = –0.022\ cm^3\ cm^{-3}$). For the VG continuous-ptfs the bias was greater for six water potentials with absolute value of $MEP' \leq 0.020\ cm^3\ cm^{-3}$ except for $\theta_{1.5}$ ($MEP' = 0.004\ cm^3\ cm^{-3}$) (Table 7). The precision was poor for the simple and VG Continuous-ptfs ($0.030 \leq SDP' \leq 0.044\ cm^3\ cm^{-3}$) but results showed that SDP decreased with the water potential.

Comparison of the class- and continuous-ptfs

Results showed very little difference between the ptfs studied. The bias recorded was small ($–0.008 \leq MEP \leq 0.002\ cm^3.cm^{-3}$) and the greatest absolute value of bias was recorded with the VG continuous-ptfs ($MEP = –0.008\ cm^3.cm^{-3}$). On the other hand, the precision was poor ($0.039 \leq SDP \leq 0.045\ cm^3.cm^{-3}$), the greatest precision being recorded with the two types of continuous-ptfs studied. If the VG Continuous-ptfs led to the greatest precision ($SDP = 0.039\ cm^3.cm^{-3}$), they led also the greatest value of bias ($MEP = –0.008\ cm^3.cm^{-3}$).

Conclusion

Our results showed that textural class-ptfs led to prediction performance that are similar to those recorded with more sophisticated class-ptfs and with continuous-ptfs. Thus without knowing the particle size distribution, organic carbon content and bulk density as required by most ptfs, we can predict the water retention properties with similar prediction quality by using the texture alone. Our results showed also that use of both texture and bulk density slightly increase the precision when compared to the precision recorded with the textural class-ptfs. Finally, we showed also that class-ptfs, including very simple ptfs, should be still considered as useful tools for predicting the water retention properties of soils, particularly at scales for which semi-quantitative or qualitative basic soil characteristic such as the texture are the only characteristic available. More generally, our results pointed out that discussion of ptfs performance should refer to those recorded with simple ptfs, thus enabling to quantify how much prediction bias and precision can be gained when increasing the complexity of ptfs and consequently the number and quality of predictors required.

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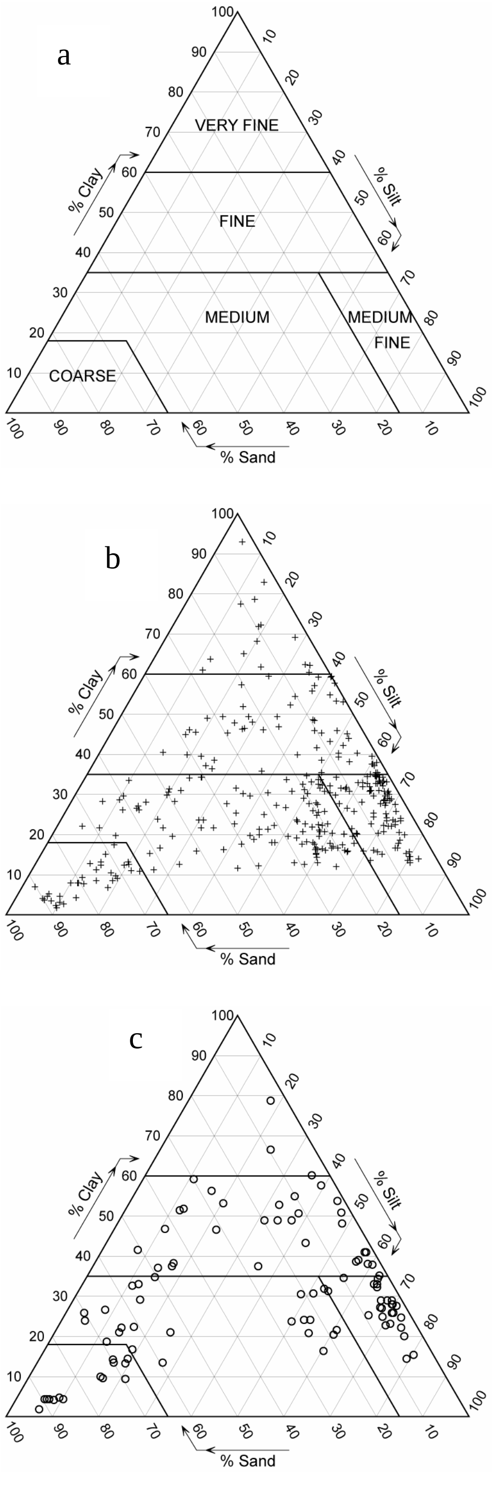

Fig. 1: Triangle of texture used (a), texture of the horizons used to develop the class- and continuous-ptfs (b) and texture of those used to test their validity (c).

Fig. 1 : Triangle de texture utilisé (a), texture des horizons utilisés pour développer les classes de fpt et les fpt continues (b) et texture des horizons utilisés pour discuter leur validité (c).

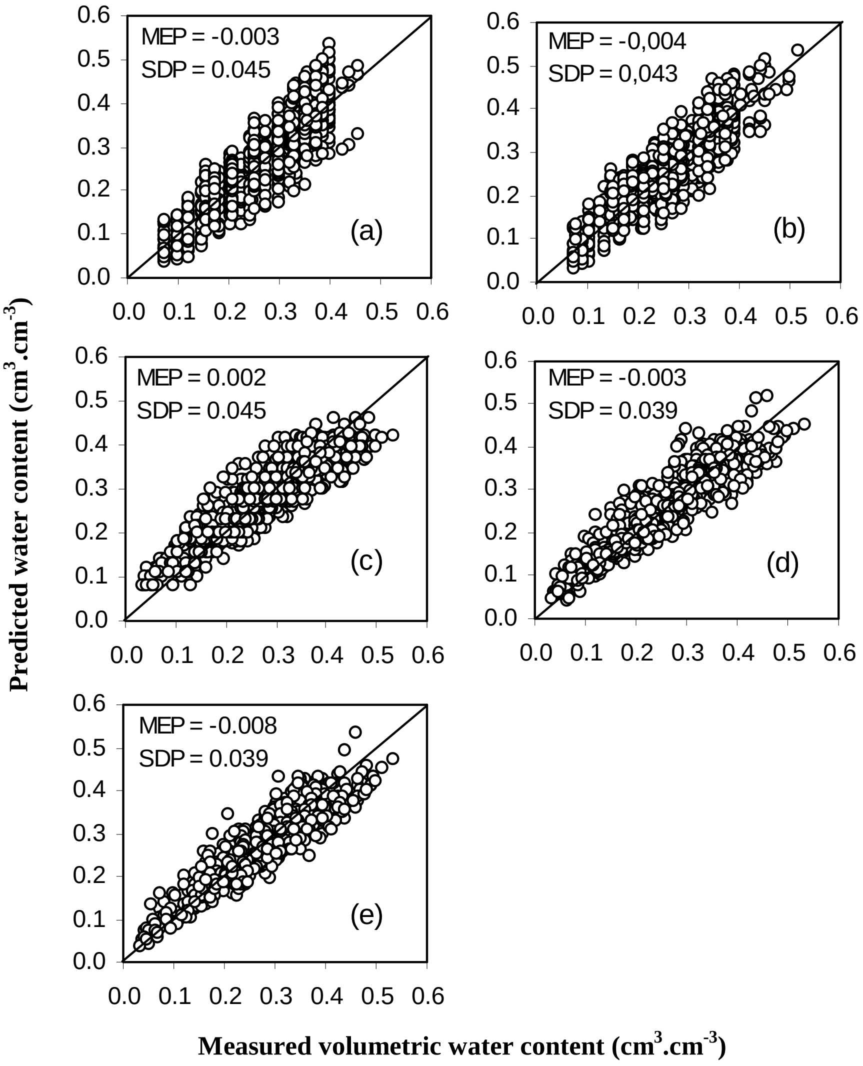

Fig. 2: Validity of the textural class-ptfs (a), texturo-structural class-ptfs (b), VG textural class-ptfs (c), continuous-ptfs (d), and VG continuous-ptfs (e) developed.

Fig. 2 : Validité des classes de fpt texturales (a), texturo-structurales (b) et VG texturales (c), ainsi que des fpt continues (d) et VG continues.

Table 1
Characteristics of the horizons of the data set used to develop the ptfs and of the test data set.
Tableau 1
Caractéristiques des horizons de l’ensemble de données utilisé pour développer les fpt et de celui utilisé pour en discuter la validité.

	Particle size distribution (%)			OC g.kg^{-1}	CaCO$_3$ g.kg^{-1}	CEC cmol$_c$kg^{-1}	D$_b$ g.cm^{-3}	Volumetric water content (cm^3 cm^{-3})						
	<2 µm	2-50 µm	50-2000 µm					$\theta_{1.0}$	$\theta_{1.5}$	$\theta_{2.0}$	$\theta_{2.5}$	$\theta_{3.0}$	$\theta_{3.5}$	$\theta_{4.2}$
Horizons used to establish class- and continuous-ptfs (n=320)														
mean	28.9	46.2	24.9	5.7	65	14.3	1.53	0.350	0.335	0.316	0.289	0.257	0.220	0.179
s.d.	15.1	20.8	23.9	4.9	189	8.0	0.15	0.067	0.065	0.070	0.070	0.075	0.074	0.070
min.	1.9	2.8	0.1	0.0	0.0	0.8	1.00	0.123	0.100	0.080	0.056	0.048	0.033	0.013
max.	92.9	82.1	90.1	28.8	982	52.8	1.84	0.606	0.596	0.586	0.558	0.510	0.462	0.370
Horizons used to test the ptfs (n=107)														
mean	30.2	40.6	29.2	6.6	38	15.8	1.51	0.356	0.332	0.312	0.287	0.261	0.224	0.202
s.d.	15.4	24.3	28.6	5.3	134	10.8	0.13	0.075	0.079	0.082	0.084	0.086	0.083	0.080
min.	1.9	4.1	1.6	0.0	0.0	0.6	1.10	0.161	0.121	0.099	0.072	0.045	0.041	0.033
max.	78.7	80.3	91.8	28.2	656	50.2	1.77	0.534	0.498	0.482	0.457	0.440	0.396	0.369

Table 2
Textural class-ptfs developed.
Tableau 2
Classes de fpt texturales développées.

	Volumetric water content (cm^3 cm^{-3})						
	$\theta_{1.0}$	$\theta_{1.5}$	$\theta_{2.0}$	$\theta_{2.5}$	$\theta_{3.0}$	$\theta_{3.5}$	$\theta_{4.2}$
Very fine (n = 15)	0.455	0.437	0.424	0.402	0.385	0.357	0.322
Fine (n = 60)	0.399	0.388	0.373	0.351	0.331	0.301	0.254
Medium fine (n = 96)	0.356	0.342	0.327	0.298	0.254	0.210	0.173
Medium (n = 117)	0.334	0.320	0.302	0.273	0.242	0.203	0.156
Coarse (n = 32)	0.249	0.224	0.181	0.149	0.120	0.100	0.076

Table 3
Texturo-structural class-ptfs developed.
Tableau 3
Classes de fpt texturo-structurales développées.

		Volumetric water content (cm^3 cm^{-3})						
		$\theta_{1.0}$	$\theta_{1.5}$	$\theta_{2.0}$	$\theta_{2.5}$	$\theta_{3.0}$	$\theta_{3.5}$	$\theta_{4.2}$
Very Fine (n =15)	$1.10 \leq D_b < 1.30$	0.498	0.473	0.451	0.423	0.405	0.371	0.330
	$1.30 \leq D_b < 1.50$	0.459	0.439	0.428	0.405	0.385	0.352	0.328
	$1.50 \leq D_b < 1.70$	0.359	0.359	0.361	0.353	0.347	0.340	0.294
Fine (n = 32)	$1.00 \leq D_b < 1.20$	0.519	0.499	0.494	0.461	0.431	0.373	0.281
	$1.20 \leq D_b < 1.40$	0.452	0.443	0.421	0.385	0.373	0.340	0.271
	$1.40 \leq D_b < 1.60$	0.391	0.378	0.361	0.344	0.321	0.289	0.250
	$1.60 \leq D_b < 1.80$	0.338	0.334	0.325	0.307	0.291	0.275	0.244
Medium Fine (n = 96)	$1.20 \leq D_b < 1.40$	0.348	0.338	0.323	0.291	0.232	0.188	0.153
	$1.40 \leq D_b < 1.60$	0.359	0.343	0.328	0.298	0.258	0.211	0.175
	$1.60 \leq D_b < 1.80$	0.353	0.345	0.329	0.303	0.263	0.230	0.190
Medium (n = 117)	$1.20 \leq D_b < 1.40$	0.354	0.337	0.314	0.278	0.245	0.193	0.140
	$1.40 \leq D_b < 1.60$	0.346	0.329	0.310	0.275	0.235	0.193	0.146
	$1.60 \leq D_b < 1.80$	0.320	0.307	0.293	0.270	0.248	0.214	0.167
	$1.80 \leq D_b < 2.00$	0.296	0.289	0.274	0.266	0.258	0.231	0.186
Coarse (n = 32)	$1.40 \leq D_b < 1.60$	0.241	0.210	0.164	0.135	0.106	0.093	0.075
	$1.60 \leq D_b < 1.80$	0.253	0.231	0.188	0.156	0.126	0.103	0.077

Table 4
Parameters of the van Genuchten's model corresponding to the VG textural class-ptfs developed according to the type of horizon (topsoil and subsoil).
Tableau 4
Paramètres du modèle de van Genuchten correspondant aux classes de ptf VG texturales développées en fonction du type d'horizon (horizon de surface et horizon de subsurface).

	θr	θs	α	n	m
Topsoils					
Coarse	0,025	0,397	1,0592	1,1530	0,1327
Medium	0,010	0,428	0,4467	1,1000	0,0909
Medium fine	0,010	0,465	0,6860	1,1027	0,0931
Fine	0,010	0,477	0,6153	1,0652	0,0612
Very Fine	0,010	0,587	5,9433	1,0658	0,0617
Subsoils					
Coarse	0,025	0,367	1,0535	1,1878	0,1581
Medium	0,010	0,388	0,1851	1,0992	0,0903
Medium fine	0,010	0,416	0,1611	1,0978	0,0891
Fine	0,010	0,437	0,1334	1,0632	0,0594
Very Fine	0,010	0,472	0,0745	1,0499	0,0475

Table 5
Regression coefficients and coefficient of determination R^2 recorded for the continuous-ptfs developed.
Tableau 5
Coefficients de régression et coefficients de détermination R^2 enregistrés pour les ptf continues développées.

	Water potential (hPa)						
	-10	-33	-100	-330	-1000	-3300	-15000
a	0.4701^{***}	0.3556^{***}	0.2620^{***}	0.1301^{***}	0.0184	-0.0504	-0.0786^{**}
b	0.0026^{***}	0.0029^{***}	0.0034^{***}	0.0038^{***}	0.0045^{***}	0.0047^{***}	0.0045^{***}
c	0.0006^{***}	0.0008^{***}	0.0012^{***}	0.0012^{***}	0.0008^{***}	0.0005^{***}	0.0003^{***}
d	-0.0006	-0.0002	0.0002	0.0010	0.0017^{***}	0.0012^{**}	0.0004
e	-0.1447^{***}	-0.0939^{***}	-0.0647^{***}	-0.0084	0.0398^{*}	0.0697^{***}	0.0710^{***}
R^2	0.59	0.64	0.69	0.74	0.77	0.82	0.86

$\theta = a + (b\times\%Cl) + (c\times\%Si) + (d\times\%OC) + (e\times D_b)$ with θ volumetric water content at a given water content.
*** P = 0.001. ** P = 0.01. * P = 0.05.

Table 6
VG continuous-ptfs developed for the parameters of the van Genuchten's model.
Tableau 6
Relations correspondent aux fpt VG continues développées pour les paramètres du modèle de van Genuchten.

$\boldsymbol{\theta}_s = 1.1658 - 0.0032*C - 0.4737*D + 2*10^{-7}*S^2 - 0.0001*OC^2 + 0.0373*C^{-1} + 0.0131*S^{-1} - 0.0072*\ln(S) + 0.00003*OC*C + 0.0022*D*C - 0.0002*D*OC - 0.0001*S$
($R^2 = 0.95$)

$\boldsymbol{\alpha}^* = 25.61 + 0.0439*C + 0.1129*S + 1.1914*OC + 32.21*D - 10.48*D^2 - 0.0009*C^2 - 0.0146*OC^2 - 0.3781*OC^{-1} - 0.0178*\ln(S) - 0.1032*\ln(OC) - 0.1*D*S - 0.6001*D*OC$
($R^2 = 0.26$)

$\boldsymbol{n}^* = -15.29 - 0.0659*C + 0.0115*S - 0.2115*OC + 12.33*D - 1.3578*D^2 + 0.0006*C^2 + 0.0031*OC^2 + 4.0005*D^{-1} + 2.2003*S^{-1} + 0.1643*OC^{-1} - 0.1205*\ln(S) + 0.2693*\ln(OC) - 9.9367*\ln(D) + 0.003*D*C + 0.0694*D*OC$
($R^2 = 0.35$)

θ_s is a model parameter, α^*, n^* are transformed model parameters in the Mualem-van Genuchten equations; C = percentage clay (i.e., percentage < 2 µm); S = percentage silt (i.e., percentage between 2 µm and 50 µm); OC = organic carbon g.kg^{-1}; D = bulk density.

Table 7
Validity of the continuous- and class-ptfs according to the water potential.
Tableau 7
Validité des classes de fpt et des fpt continues aux différentes valeurs de potentiel de l'eau.

	Volumetric water content ($cm^3.cm^{-3}$)													
	Mean Error of Prediction (*MEP'*)							Standard Deviation of Prediction (*SDP'*)						
	$\theta_{1.0}$	$\theta_{1.5}$	$\theta_{2.0}$	$\theta_{2.5}$	$\theta_{3.0}$	$\theta_{3.5}$	$\theta_{4.2}$	$\theta_{1.0}$	$\theta_{1.5}$	$\theta_{2.0}$	$\theta_{2.5}$	$\theta_{3.0}$	$\theta_{3.5}$	$\theta_{4.2}$
Textural class-ptfs	-0.006	0.004	0.003	0.001	-0.004	-0.001	-0.020	0.046	0.046	0.044	0.045	0.047	0.044	0.042
Texturo-structural class-ptfs	-0.006	0.002	0.002	0.001	-0.005	-0.002	-0.019	0.042	0.042	0.041	0.043	0.045	0.044	0.041
VG class-ptfs	0.014	0.007	-0.003	-0.008	-0.007	0.007	0.002	0.045	0.045	0.045	0.046	0.046	0.043	0.040
Continuous-ptfs	-0.006	0.001	0.005	0.001	-0.003	0.002	-0.022	0.044	0.044	0.040	0.039	0.036	0.032	0.030
VG continuous-ptfs	0.012	0.004	-0.008	-0.017	-0.020	-0.008	-0.016	0.044	0.041	0.038	0.039	0.035	0.033	0.032