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Predicting soil water retention characteristics for Vietnam Mekong Delta soils

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Abstract Soil hydraulic properties (e.g. soil water retention and hydraulic conductivity) are very important for agricultural and environmental management practices. However, the direct field or laboratory measurement of these characteristics is costly, laborious and time-consuming. Therefore, their indirect estimation from available and easily measured soil properties has received great interest. Pedotransfer functions (PTFs) are being used as a well-known indirect method for determining hydraulic properties from basic soil properties (e.g. soil texture, bulk density and organic carbon content). In this study, we derived two types of PTFs, point and pseudo-continuous functions, for estimating moisture retention characteristics of soils in the Mekong Delta of Vietnam. The data of 120 samples were collected from agricultural fields distributed over the area. The results reveal that point PTFs outperformed pseudo-continuous functions. Moreover, the plastic limit, on top of classical predictors, appears to be a promising variable to predict soil water retention, especially in the wet moisture range.

Key words pedotransfer functions; soil water retention; pseudo-continuous PTF; plastic limit; tropical delta soils

INTRODUCTION

Except for the availability of large databases which boosted the development of pedotransfer functions (PTFs) in temperate regions, there are few well-documented and exhaustive databases for soils in the tropics (Minasny & Hartemink, 2011). This lack of availability challenges the development of hydraulic PTFs and leads to difficulties of applying water and solute transport simulation models in tropical regions. Moreover, due to the specific agro-pedo-climatic dependence of PTFs, published PTFs developed based on temperate soil databases should not be applied for soils in tropical regions without considering their validation and calibration (Hodnett & Tomasella, 2002). Therefore, PTFs should be used as an interpolation technique to predict a desired property of soils belonging to the range from whose data the PTF was developed, rather than as an extrapolation tool for estimation of soils outside that range (Lilly & Lin, 2004).

During the past decade, considerable progress has been made in developing hydraulic PTFs for tropical soils, as is illustrated by studies of Mdemu & Mulengera (2002), Suprayogo *et al.* (2003), Jabloun & Sahli (2006), Adhikary *et al.* (2008), Aimrun & Amin (2009), Minasny & Hartemink (2011), Obalum & Obi (2012), Shwetha & Varija (2012), Botula *et al.* (2013) and Patil *et al.* (2013). However, little effort was devoted to tropical delta soils.

The main agricultural practice in the tropical Mekong delta of Vietnam is paddy rice cultivation. The soil is usually prepared under submerged conditions generating the typical massive plough layer. The physical and hydraulic soil characteristics of the puddled layers are tremendously different when compared to those under other land use types.

Because of the very specific nature of these soils and representative agricultural practices, the soil water characteristics in the tropical delta cannot be estimated by utilizing published PTFs reported so far in literature. The objective of this study was to develop predictive functions for estimating the soil water retention characteristics in deltas dominated by rice cultivation based on basic soil properties which are usually available in many soil datasets (e.g. soil texture, bulk density and organic matter content). Additionally, as soil water retention PTFs of tropical soils are now in the development stage, we examined whether using other available and easily measurable soil properties (e.g. plastic limit, soil aggregate stability index) on top of the classical soil properties can increase PTF's predictability. To our knowledge, this is the first study focusing on prediction of soil water retention properties of a variety of soils in a tropical delta dominated by rice paddy cultivation.

MATERIALS AND METHOD

Soil dataset

A dataset of 120 samples was constructed for establishing functions to estimate soil water retention from other easily measurable soil properties in the Mekong Delta. Disturbed and undisturbed samples were randomly taken from two upper diagnostic horizons in agricultural fields (mainly rice paddy, but also upland crops such as sugarcane, maize and fruit orchard). The soil samples were collected with the aim of covering a wide range of major soils groups primarily exploited for agricultural production in the Mekong Delta. These samples belonged to the following World Reference Base soil groups: Fluvisols, Gleysols, Luvisols, Arenosols, and Plinthosols (FAO, 2006).

The undisturbed soil samples, taken in standard sharpened steel cylinders of approx. 100 cm^3 volume, were used to determine soil bulk density (core method; volume at soil sampling) and soil water retention characteristics (using sandbox apparatus for determining water retention at low pressure heads of –10, –30, –60, –100 cm, and pressure chambers for high pressure heads of –200, –330, –1000, –15 000 cm according to the procedures outlined in Cornelis *et al.*, 2005). The disturbed soil samples which were taken from near the undisturbed sampling pits, were used to determine other chemical and physical soil properties, including organic carbon content by the Walkley & Black method (Walkley & Black, 1934), particle size distribution by sieve-pipette method (Gee & Bauder, 1986), soil aggregate stability by dry and wet sieving method (described by Le Bissonnais, 1996) and plastic limit (ASTM Standard D4318, 2010).

The statistics of the dataset are given in Table 1. The variation in soil texture is graphically illustrated in the USDA soil textural triangle (Fig. 1). Soils in the dataset have textures ranging from sand to clay, in which large proportions (about 72%) are fine textured soils (defined as the texture classes: clay, clay loam, silty clay, silty clay loam, all having more than 35% clay). The remaining 28% belong to medium to coarse textures.

Predicting soil water retention

Two types of regression functions were constructed by using variables of our dataset. The first type comprises “point” PTFs, in which functions are built to predict water content at specific pressure heads (eight heads in our study, corresponding to eight datasets with N = 120, with N the number of soil samples taken). The second type refers to “pseudo-continuous” PTFs as first introduced by Haghverdi *et al.* (2012) for Artificial Neural Networks, in which the log of pressure head is one of the predictors, hence allowing prediction of water content at any desired pressure head ($N \times M = 120 \times 8 = 960$, with M the number of pressure heads considered in the determination of the water retention curve).

Table 1 Minimum, maximum, mean value and standard deviation of soil variables used to develop soil water retention PTFs.

Soil properties	Min	Max	Mean	Std. Deviation
Organic carbon (OC) (%)	0.08	12.26	2.20	2.66
Bulk density (BD) (kg/m^3)	0.75	1.90	1.29	0.25
Sand content (S) (%)	0.4	98.6	20.1	29.7
Silt content (Si) (%)	0.0	61.0	38.2	14.5
Clay content (C) (%)	1.4	73.9	41.7	20.6
Plastic limit (PL) (g/g)	0.14	0.72	0.33	0.10
Stability index (SI)	0.3	7.69	1.39	1.12
θ (m^3/m^3) at h = –10 cm	0.24	0.75	0.49	0.11
θ (m^3/m^3) at h = –30 cm	0.18	0.72	0.47	0.11
θ (m^3/m^3) at h = –60 cm	0.12	0.71	0.45	0.12
θ (m^3/m^3) at h = –100 cm	0.06	0.70	0.44	0.13
θ (m^3/m^3) at h = –200 cm	0.04	0.55	0.34	0.11
θ (m^3/m^3) at h = –330 cm	0.03	0.55	0.33	0.11
θ (m^3/m^3) at h = –1000 cm	0.03	0.49	0.29	0.11
θ (m^3/m^3) at h = –15000 cm	0.02	0.33	0.21	0.08

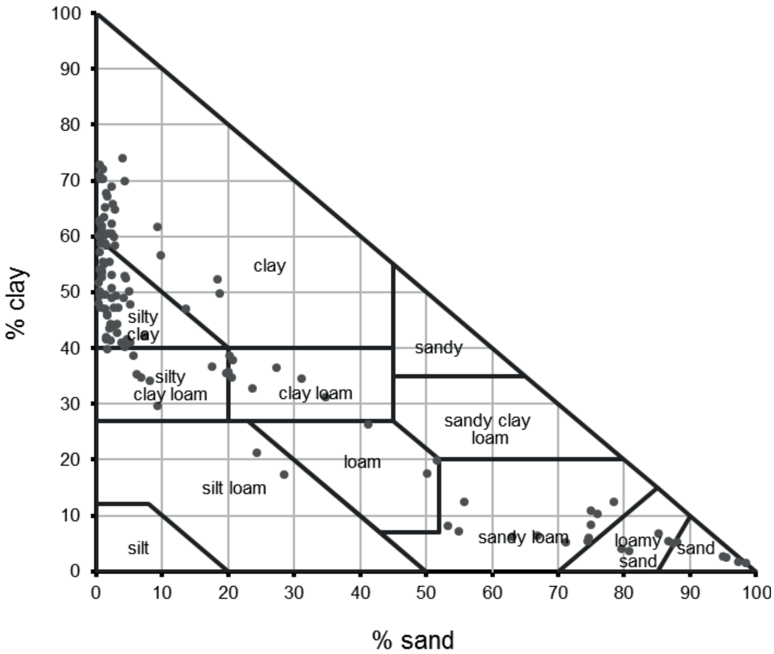

Fig. 1 Variation of soil texture classes in the dataset (N = 120).

Preliminary data analysis developed an exponential curve for the relationship between total organic carbon content and soil moisture content. Therefore, we applied a log-transformation to resolve this problem before we conducted multiple linear regression (MLR) analysis. SPSS version 20 was used to develop regression equations for predicting the soil water retention characteristic. First, both types of PTFs were developed with classical independent variables (soil texture, bulk density and total organic carbon content). Then, more variables (soil aggregate stability and plastic limit) were added to the independent set of predictors in an attempt to increase the point PTF's predictability.

Evaluating the accuracy of prediction

Once the multiple linear regression equations were developed based on the different types of datasets, their performance and accuracy in predicting soil water retention characteristics was quantified by the scatter plot of measured *versus* predicted moisture content with 1:1 reference line, and in the combination with other statistical indices such as root mean square error (RMSE), and coefficient of determination (R^2)

RMSE and R^2 are defined as:

$$\text{RMSE} = \sqrt{\frac{1}{N}\sum_{i=1}^{n}\left(E_i - O_i\right)^2} \tag{1}$$

$$R^2 = \frac{\left[\text{cov}(O_i, E_i)\right]^2}{\text{var}(O_i) * \text{var}(E_i)} \tag{2}$$

where E_i is the *i*th estimated value, O_i is the *i*th observed value, N (which should be replaced by $N \times M$ in case of the "pseudo-continuous PTF") is the number of observations and var and cov denote the variance and covariance functions of measured and estimated values, respectively.

RMSE (equation (1)) is a measure of the overall prediction error. R^2 (equation (2)) refers to the strength of the linear relationship between measurement and prediction, which indicates the amount of variability explained by the regression equation.

RESULTS AND DISCUSSION

Performance of point and pseudo-continuous predictions

The list of predictor variables in the PTFs which were automatically selected by stepwise regression and the corresponding coefficient of determination, R^2, of the regression equations are enumerated in

Table 2. It confirms the importance of widely-used water retention PTF predictors such as soil organic carbon content, soil texture and bulk density in explaining the variability of soil water retention characteristics (supporting studies of Gupta & Larson (1979); Rawls *et al.* (2003); Jabloun & Sahli, 2006; Shwetha & Varija, 2012). Point PTFs show that in the wet and intermediate moisture range, moisture retention is basically related to macrostructure (e.g. bulk density, OC, soil texture), whereas specific surface area (e.g. clay and OC content) inherently links to water retention at low matric potentials. In their review on PTFs, Wösten *et al.* (2001) also highlighted the advantages of point PTFs in offering insight knowledge of relevant relationships between soil water retention characteristics and other soil properties.

The entire soil water characteristic curve could be defined reasonably well (R^2 = 0.87) by the pseudo-continuous PTF which employed the logarithmic form of matric potential and total organic carbon content, soil texture (clay and silt content), and bulk density as crucial predictors. On the other hand, soil water content at the given matric heads is satisfactorily estimated by a particular functional form of these basic soil properties ($0.80 < R^2 < 0.90$). Such high values of R^2 suggest the appropriateness of the PTFs in describing the behaviour of soil moisture retention characteristics. The graphical representation of measured *versus* predicted values of soil water retention of both PTF types with the 1:1 reference line (Fig. 2) also displays a good agreement between them. Notwithstanding this, point PTFs are considerably better than the pseudo-continuous function. All the points of measured *versus* predicted values derived by point PTFs are closely scattered around the reference line, and do not exhibit much bias. The plot of pseudo-continuous PTFs reveals, however, an over-estimation in the dry moisture range, and an under-estimation in the wet moisture range.

Table 2 List of point and pseudo-continuous PTFs and their corresponding R^2 developed by using classical predictors.

Matric head (cm)	PTFs*	R^2
–10	0.57 + 0.06*log(OC) + 0.002*C – 0.14*BD	0.80
–30	0.52 + 0.07*log(OC) + 0.002*C – 0.13*BD	0.80
–60	0.31 + 0.15*log(OC) + 0.003*C	0.85
–100	0.14 + 0.18*log(C) + 0.14*log(OC)	0.87
–200	0.08 + 0.22*log(C) – 0.05*BD	0.86
–330	0.08 + 0.22*log(C) – 0.06*BD	0.87
–1000	0.06 + 0.22*log(C) – 0.08*BD	0.90
–15300	0.02 + 0.003*C + 0.001*Si	0.89
At any matric head	0.48 + 0.003*C – 0.1*log(h) + 0.05*log(OC) + 0.001*Si – 0.05*BD	0.87

*OC is organic carbon content in % by weight, BD is bulk density in $Mg.m^{-3}$, C is clay content in % by weight, Si is silt content in % by weight, h is matric head in cm water.

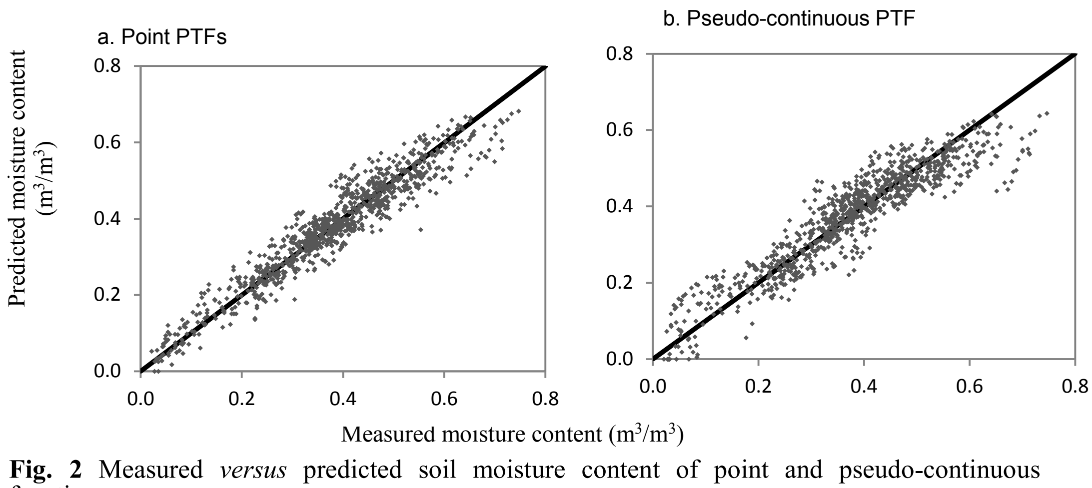

Fig. 2 Measured *versus* predicted soil moisture content of point and pseudo-continuous functions.

Pseudo-continuous PTFs, however, have the advantage that they allow the estimation of water content directly at any pressure head of the soil water retention curve. Haghverdi *et al.* (2012) also found that their ANN's pseudo-continuous PTFs performed slightly better than point PTFs when limited data were available. The reasons they explained for such results is the fact that a pseudo-continuous PTF increased the size of the dataset with a factor equal to the number of matric potentials used to describe the soil water retention curve. This feature appears to influence the accuracy of PTFs developed by ANNs, a large database demanding technique, in contrast to point PTFs.

Our finding, alternatively confirms the results of Tomasella *et al.* (2003) and Vereecken *et al.* (2010). These authors point out that moisture content at different pressure heads is controlled by different soil properties, and therefore, point PTFs should provide a better combination of these properties leading to more accurate functions for estimation.

PTF's accuracy

In evaluating the prediction accuracy of our derived PTFs, Fig. 3 shows that point PTFs result in more accurate estimations than pseudo-continuous PTFs. The RMSE of point PTFs across different pressure heads is always lower than that of pseudo-continuous PTFs at the same pressure head, especially in the dry moisture range. We found the highest value of RMSE at log(h) of 2 (h = –100 cm) in both types of PTFs. This finding is supported by the same observations found by Rajkai & Varallyay (1992), who reported lowest accuracy somewhere between –10 to –100 kPa. Moreover, Cornelis *et al.* (2001) also indicated that the prediction error for soil moisture retention is usually large at high and intermediate matric potential. Generally, we obtained the most accurate estimations in the dry moisture range. The lowest RMSE value at low matric potential is probably due to the inherent low water content retained in the soil which leads to lesser variation between measurement and prediction compared to that in the wet and intermediate range (Nemes *et al.*, 2006). Moreover, water retention in the wet moisture range is primarily determined by soil structure, which is to a lesser extent related to basic soil properties as well as being affected by several external factors (Kay & Angers, 2002).

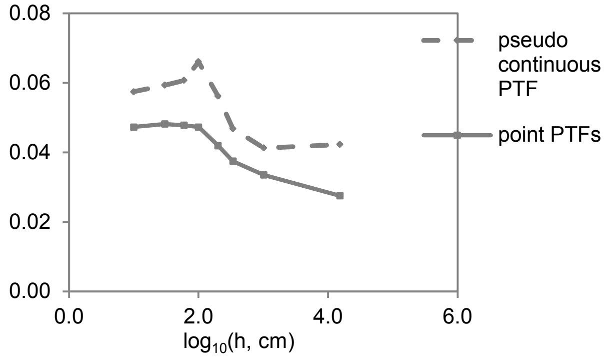

Fig. 3 Variation of the root mean squared error (RMSE) as a function of pressure head.

Effects of supplementary predictors

Stepwise multiple linear regression analysis on the dataset containing classical predictors as well as supplementary predictors, like soil aggregate stability and plastic limit, showed that soil plasticity had a significant linear relationship with soil moisture at high matric potential (from –1 kPa to –10 kPa). Aggregate stability had no significant effect. Incorporating the plastic limit in the regression equations slightly increased the accuracy of soil water estimation, especially in the wet moisture range. With plastic limit as an additional predictor, RMSE at high matric potentials (–1, –3, –6, –10 kPa) reduced from a range of 0.047 to 0.048 (Fig. 3), to a range of 0.044 to 0.045. However, when using plastic limit as predictor for estimating soil water retention characteristics, we simultaneously omitted the non-plastic soils (normally coarse-textured soils) in our dataset.

Therefore, this property is partially useful for determination of the soil water retention of plastic soils. Nonetheless, this finding is significant because the determination of plastic limit is very simple and does not require any specialized devices. Thus exploiting this property as a potential predictor could be of great importance in the development and application of hydraulic pedotransfer functions in developing countries such as Vietnam.

CONCLUSION

The present study proposes highly applicable point and pseudo-continuous PTFs for estimating soil water retention characteristics for young and fertile tropical delta soils which are mainly used for paddy rice cultivation. One pseudo-continuous equation could be used to predict soil water retention at any desirable matric potential of soil water retention curve. However, point PTFs offer more accurate estimation of soil at the specific matric potentials. Moreover, the plastic limit, on top of classical predictors, appears to be a promising variable to predict soil water retention at high matric heads for plastic-performed soils.

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