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Pedotransfer Functions for the Estimation of the Field Capacity and Permanent Wilting Point

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Abstract: The objective of this study was to develop regression models or equations to estimate the field capacity and permanent wilting point, which are the soil moisture characteristics, by means of the particle size distribution and bulk density. The particle size distribution and bulk density were considered as independent variables in the regression equations. A significant negative relationship between the field capacity and sand fraction and bulk density and between the permanent wilting point and sand fraction and bulk density was determined ($P<0.001$), whereas a significant positive relationship between the field capacity and clay and silt fractions and between the permanent wilting point and clay and silt fractions was found ($P<0.001$). The determination coefficients were in the range of 92-97% for the determination of the field capacity and permanent wilting point.

Key words: Field capacity, permanent wilting point, particle size distribution, bulk density

INTRODUCTION

The movement, storage and availability of water in soil must be known for planning of irrigation systems. Soil water retention is defined by capillarity, which is the result of adhesion and cohesion. In addition, capillarity depends on the structure of the soil pores. The extent of soil water retention controlled by soil structure, clay type, organic mater content and soil compaction. Especially soils with high montmorillonit clay content have great water retention capacity[1].

The water retention curve, which defines the relationship between the soil water content and hydraulic potential, is an important characteristic of soils. Direct determination of this property can be expensive and time consuming. Since water retention of soil is affected by physical properties, such as texture and structures, it is possible to develop empirical relationships to predict soil water retention. Developments in the computer modeling accelerate these studies[2]. Bouma[3] introduced the term pedotransfer function (PTF) and described it as translating available data into the requirement. For instance, predictive functions of certain soil properties from some other properties can be determined easily and cheaply.

In the past, attempts were made to correlate basic soil properties such as size fractions (sand, silt and clay) and organic carbon with water content held at certain hydraulic potentials (usually at 1/3 atm and 15 atm). This was made in order to estimate water content at field capacity and permanent wilting point and the availability of soil water to plants[4].

Minansny *et al.*[2] presented three types of PTF: 1) Point estimation: This PTF is an empirical function that predicts the water content at a pre-defined potential. The most common method used in the point estimation PTF is to employ multiple linear regressions. 2) Parametric estimation: Parametric PTF is based on the assumption that Q (h) relationship described adequately by a hydraulic model that is a closed form equation with a certain number of parameters. 3) Psycho-empirical model: In this approach, water retention curve is derived from physical attributes. Arya and Paris[5] translated the particle size distribution into a water-retention curve by solid mass fractions to water content and pore-size distribution into hydraulic potential by means of a capillary equation. The problem with this method is the need for information about the packing of soil particles.

Tyler and Wheatcraft[6] reported that Arya and Paris model is shown to be physically based and should be improved for efficient estimation of water retention data where field or laboratory measurements are not available.

Batjes[7] developed a model for predict soil water content at different pressure head with multiple linear regression. The correlation coefficients were 0.88 and 0.90 for the pF:4.2 and the other pressure heads, respectively. Similarly, Rawls *et al.*[8] presented regression equations for the estimation of the soil water content at different water

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potentials in soils with different particle size distribution. The general form of the linear regression equations is:

$$\theta_p = a+b\ (\text{sand }\%)+c\ (\text{silt }\%)+d\ (\text{clay }\%)+ e\ (\text{organic matter }\%)+f(\text{bulk density, mg m}^{-3})$$

where a, b, c, d, e and f are regression coefficients.

The main objective of this study was to develop regression models by predicting water contents at field capacity and permanent wilting point, which were needed to determine plant available water content, irrigation interval and duration. For this aim we used particle size distribution and bulk density, which are measured relatively easily and inexpensively in most areas.

MATERIALS AND METHODS

The data for this study was obtained from the study of Apan[9] entitled "A Study on the Solutions of Erzincan Plain Soil and Water Resources Problems in terms of Irrigation" The Erzincan Plain located in the Eastern Anatolia region is approximately between the 38°18^1-40°42^1 east longitudes and the 39°34^1 north latitude passes the plain. The area of the plain is approximately 39085 ha. The 70% of this area is irrigable land which consists of the first, second and third class soils. The plain consists of the alluvial soils. A total of 276 soil samples were taken from 73 different soil profiles at the depth of 0-150 cm. Since the extreme values such as the outliers and soil samples taken from gravely profiles were discarded, 230 soil samples were used in the study.

The particle size distribution, bulk density and the soil moisture content at the field capacity and permanent wilting point of the soil samples were determined by the hydrometer, cylinder and pressured tray methods, respectively.

The simple and multiple-linear regression methods were used to evaluate the data[10]. The field capacity and permanent wilting point were used as dependent variables, whereas the particle size distribution and bulk density were considered as independent variables in both methods. Besides, the multiple-linear regression analysis was also performed with the Microsoft Excel following the procedure of Gomez and Gomez[11]. Curve fitting processes were continued until the least sum of squares of the residuals was obtained. Fitted planes from the multiple-linear regression analyses using the "Slide Writer" computer package Version 2.0.

RESULTS AND DISCUSSION

Soil properties: The ranges of the sand, silt and clay contents, bulk density, the field capacity (Pv) and the permanent wilting point (Pv) were 0.60-85.00, 5.00-88.20, 0.80-76.60%, 0.72-1.79 g/cm^3, 11.20-59.20, 5.00-41.70%, respectively (Table 1).

Relationships between soil properties and soil moisture characteristics: In the statistical analyses for the determination of the relationship between soil properties such as the particle size distribution and bulk density and soil moisture characteristics such as the field capacity and permanent wilting point, size fractions (sand, silt and clay) and bulk density were used as independent variables, whereas the field capacity and permanent wilting point were considered as dependent variables.

The independent variables that affected the field capacity in the decreasing order were the sand content (r^2=0.91), bulk density (r^2=0.76), clay content (r^2=0.42) and silt content (r^2=0.25) in the simple regression analysis. Arya and Paris[5] reported that large deviations, therefore, should be expected-mainly in the case of surface soil materials where aggregation, cracking and root effects may be pronounced.

A negative relationship between the field capacity and sand content and bulk density was determined, whereas a positive relationship between the field capacity and clay and silt contents was found. The relationship between the field capacity and the fractions was statistically significant in the probability level of 0.001. (Fig. 1a-d).

The independent variables that affected the permanent wilting point in the decreasing order were the sand content (r^2=0.91), bulk density (r^2=0.73), clay content (r^2=0.51) and silt content (r^2=0.19) in the simple regression analysis. A negative relationship between the permanent wilting point and sand content and bulk density was determined, whereas a positive relationship between the permanent wilting point and clay and silt contents was found. The relationship between the permanent wilting point and the fractions was statistically significant in the probability level of 0.001(Fig. 2a-d).

The sand fraction had similar effect on the variation of the field capacity and permanent wilting point. The clay fraction affected the variation in the permanent wilting point more than that of the field capacity. The particle size distribution had more effect on the soil moisture content at the permanent wilting point than the pore size distribution[12,13]. The relationship between the permanent wilting point and clay fraction was better than the relationship between the field capacity and clay fraction.

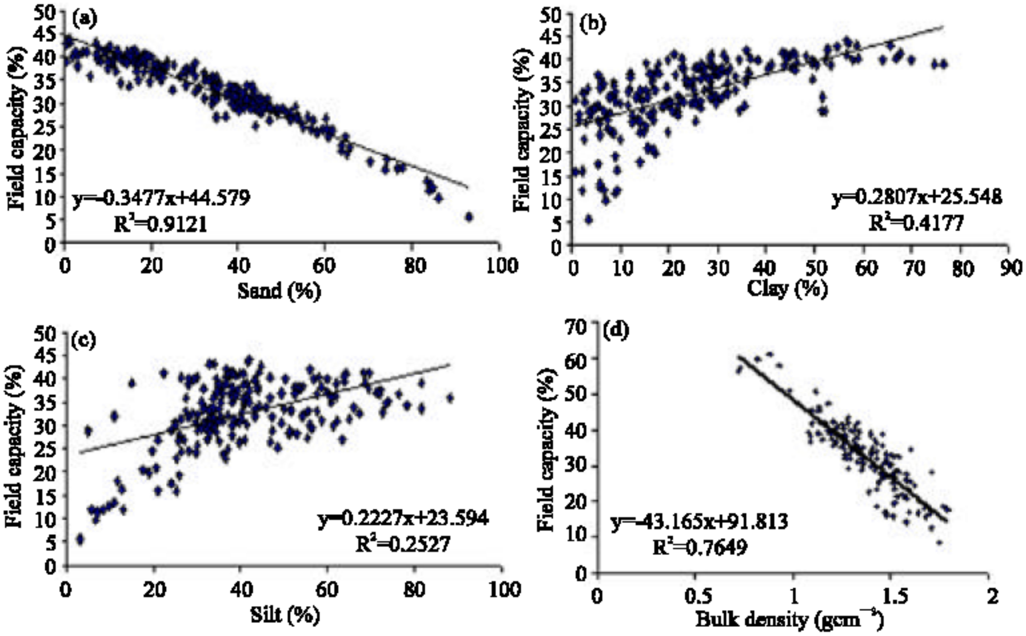

Fig. 1: The relationships between the field capacity with the particle size distribution and bulk density

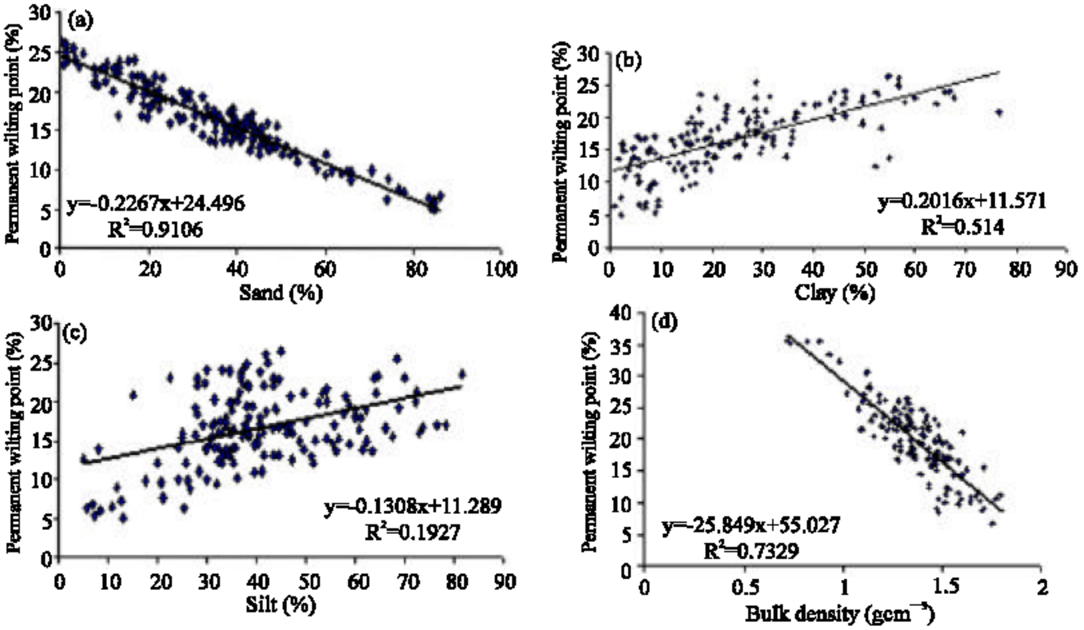

Fig. 2: The relationships between the permanent wilting point and the particle size distribution and bulk density

The silt fraction had no effect on the variation of the permanent wilting point and represented 14.3% of the variation of the field capacity and 28% of the variation of the available soil moisture capacity. In addition, Das *et al.*[14] reported that the silt fraction had effect on the available soil moisture capacity. Aina and Periaswamy[15]

Table 1: Descriptive statistics for the physical properties of the soils n:230

Soil properties	Mean	Min.	Max.	Std. dev.
Sand %	33.82	0.60	85.00	19.23
Silt %	40.92	5.00	88.20	16.30
Clay %	25.26	0.80	76.60	16.87
Bulk density g/cm^3	1.36	0.72	1.79	0.19
Field capacity %	32.90	11.20	59.20	6.83
Permanent wilting point %	16.56	5.00	41.70	4.73

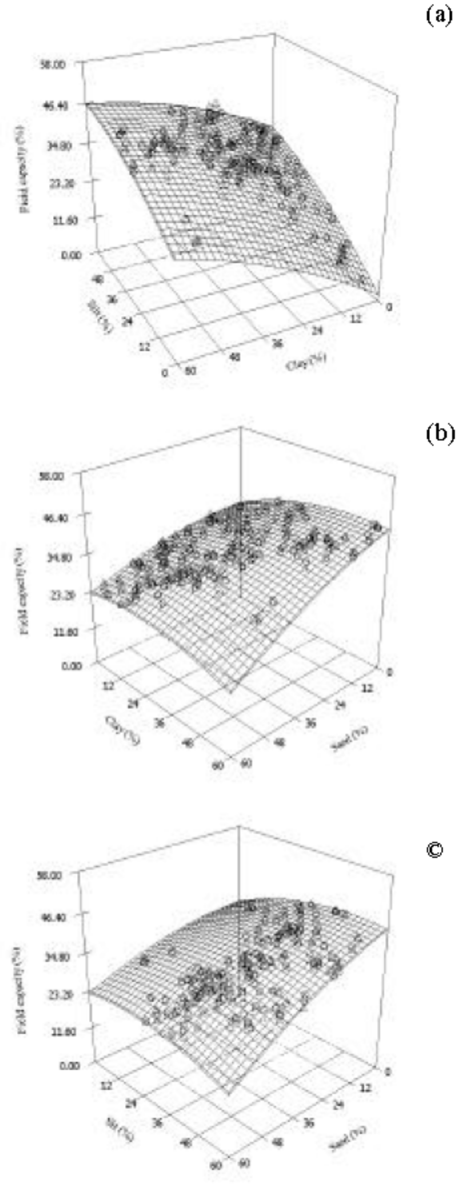

Fig. 3: The effect of sand and silt (a), clay and silt (b) and clay and sand © on the field capacity

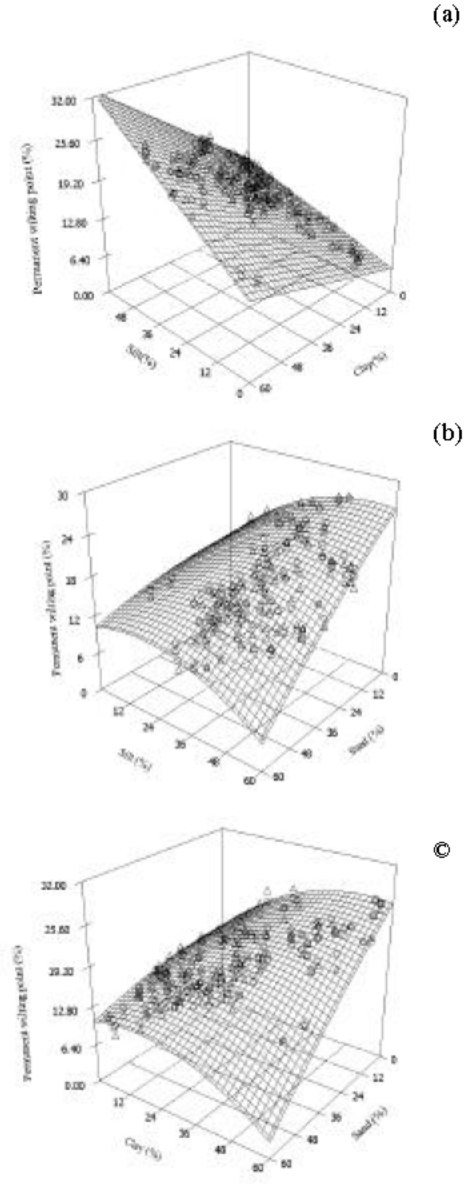

Fig. 4: The effect of sand and silt (a), clay and silt (b) and clay and sand © on the permanent wilting point

stated that field capacity can be estimated was a functions of both silt and clay contents while permanent wilting point estimated was a function of only clay content.

Because the field capacity is the soil moisture content retained in the soil pores against the gravitational force[16], there might be a close relationship between the field capacity and soil pore size distribution. The clay fraction and organic matter content might affect the field capacity positively by increasing the soil pores retaining the water against the gravitational force, whereas the sand fraction might affect the field capacity negatively by increasing the soil pores allowing the free flow of soil water. Bahtiyar[17] and Akgül and Özdemir[18] suggested that the soil moisture content at the field capacity could be estimated by utilizing these variables, which are effective on the soil pores or bulk density. Canbolat[19] investigated that the sand fraction affected the field capacity and available moisture capacity more than the permanent wilting point. However, clay content affected the permanent wilting point more than the field capacity. A negative correlation was obtained between the clay content and the field capacity and permanent wilting

Table 2: The regression models for the estimation of the field capacity from the particle size distribution n:(230)

Sand-Clay-Silt	FC=34,00624+0,00386x(SiltxClay)-0,00315x(Sand)^2
	SE=(0,3132)***(0,000214)*** (7,57x10^{-5})***
	R^2=0.97***
Silt-Clay	FC=2,082-0,00263x(SiltxClay)-0,00345x(Silt)^2-0,00322x(Clay)^2+0,6546x(Silt)+0,64x(Clay)
	SE=(0,612)***(0,00044)***(0,00026)***(0,000316)***(0,0252)***(0,0305)***
	R^2=0.97***
Sand-Silt	FC=33,97-0,00375x(SiltxSand)-0,00319x(Sand)^2-0,00402x(Silt)^2+0,393x(Silt)
	SE=(0,816)***(0,00024)***(0,00011)***(0,000351)***(0,03712)***
	R^2=0.97***
Sand-Clay	FC=33,92-0,00367x(ClayxSand)-0,00316x(Sand)^2-,00384x(Sand)^2+0,384x(Clay)
	SE=(0,348)***(0,000335)***(7,67x10^{-5})***(0,00034)***(0,0265)***
	R^2=0.97***

***P<0.001,**P<0.01, *P<0.05, FC(Field capacity), SE(Standard Error)

Table 3: The regression models for the estimation of the permanent wilting point from the particle size distribution n:230

Sand-Clay-Silt	PWP=18.74+0.00315x(SiltxClay) -0.146x(Sand)
	SE=(0.486)***(0.0032)*** (0.0076)***
	R^2=0.96***
Silt-Clay	PWP=4.22+0.0032x(SiltxClay)+0.143x(Clay)+0.145x(Silt)
	SE=(0.35)***(0.00035)***(0.013)***(0.008)***
	R^2=0.95***
Sand-Silt	PWP=14.55-0.00485x(SiltxSand)-0.0012x(Sand)^2-0.00412x(Silt)^2+0.44x(Silt)
	SE=(0.772)***(0.00022)***(0.0001)***(0.0003)***(0.035)***
	R^2=0.96***
Sand-Clay	PWP=14.96-0.00524x(ClayxSand)-0.0013x(Sand)^2-0.0043x(Clay)^2+0.44x(Clay)
	SE=(0.32)***(0.0003)***(6.97x10^{-5})***(0.00032)***(0.025)***
	R^2=0.97***

***P<0.001,**P<0.01, *P<0.05, PWP(Permanent wilting point), SE(Standard Error)

Table 4: The regression models for the estimation of the field capacity from the particle size distribution and bulk density (γ) n:230

Sand-Clay-Silt	FC=60.4 -0.11xγ^{2}xSilt -0.12xClay -0.32x γxSand
	SE=(1.62)***(0.01)*** (0.002)***(0.01)***
	R^2=0.92***
Silt-Sand	FC=82.08-27.92xγ-0.043xSilt -0.27xSand
	SE=(1.59)***(1.21)***(0.01)***(0.01)***
	R^2=0.94***
Sand-Clay	FC=77.76-27.92xγ-0.23xSand+0.04x Clay
	SE=(1.58)***(1.21)***(0.01)***(0.01)***
	R^2=0.94***
Clay-Silt	FC=73.24+0.12xγ^{2}xSilt-40.83xγ+0.25xClay
	SE=(1.40)***(0.005)***(0.93)***(0.01)***
	R^2=0.96***

***P<0.001,**P<0.01, *P<0.05, FC(Field capacity), SE(Standard Error)

Table 5: The regression models for the estimation of the permanent wilting point from the particle size distribution and bulk density (γ) n:230

Sand-Clay-Silt	PWP=32.8+0.002xγ^{2}xSand+0.14xSilt+0.17xClay -16.94xγt
	SE=(1.7)***(0.01)*** (0.02)***(0.02)***(1.1)***
	R^2=0.94***
Silt-Sand	PWP=49.2-16.76xγ -0.026xSilt -0.16xSand
	SE=(0.96)***(0.72)***(0.007)***(0.007)***
	R^2=0.94***
Sand-Clay	PWV=46.9-0.002xγ^{2}xSand-0.14xSand+0.025x Clay -16.94xγt
	SE=(1.54)***(0.01)***(0.02)***(0.007)***(1.1)***
	R^2=0.94***
Clay-Silt	PWP=43.9+0.074xγ^{2}xSilt-24.5xγt+0.15xClay
	SE=(0.84)***(0.003)***(0.006)***(0.56)***
	R^2=0.96***

***P<0.001,**P<0.01, *P<0.05, PWP(Permanent wilting point), SE(Standard Error)

point. However, a significant positive correlation was found between silt content and available moisture capacity and the field capacity. These are similar to the results of this study.

The models for the estimation of the field capacity and permanent wilting point were obtained using the particle size distribution alone and the particle size distribution and bulk density together as independent variables.

The models developed by using the particle size distribution as independent variable are given in Table 2 and 3. Four different models were obtained for the field capacity. The models included the independent variables such as sand, silt, clay, sand-silt, silt-clay clay-sand and the coefficients of determination were r^2=0.97 and statistically significant at P<0.0001. Similarly, in the models developed for the permanent wilting point, the coefficients of determination were r^2=0.95 and statistically significant at P<0.0001.

The models developed by using the particle size distribution and bulk density as independent variables are given in Table 4 and 5. Four different models were obtained for the field capacity. The models included the independent variables such as sand, silt, clay, bulk density, silt-bulk density, sand-bulk density and the correlation coefficients were in the range of 0.92-0.96 and statistically significant at P<0.0001. Similarly, in the models developed for the permanent wilting point, the correlation coefficients were in the range of 0.94-0.96 and statistically significant at P<0.0001.

Effect of sand and silt on the field capacity: The effect of sand and silt on the field capacity was expressed by the three-dimensional graph (Fig. 3a). The field capacity decreased curvilinearly as the sand fraction increased, whereas the silt fraction had no significant effect on the field capacity. As the silt fraction decreased, the field capacity increased in the high sand fractions. However, as the silt fraction increased, the field capacity increased in the low sand fractions

Effect of clay and silt on the field capacity: The increase of clay and silt fractions increased the field capacity in all cases. The highest field capacity was obtained in the high clay and silt fractions, whereas the lowest field capacity was found in the lowest clay and silt fractions (Fig. 3b).

Effect of clay and sand on the field capacity: When the relationship between the field capacity and clay and sand fractions was examined, a significant relationship between the field capacity and clay fraction was observed (Fig. 3c).

The field capacity increased as the clay fraction decreased in the high sand fractions, whereas the field capacity increased as the clay fraction increased in the low sand fractions. The highest field capacity was determined in the low sand and high clay fractions, whereas the lowest field capacity was obtained in the high clay and sand fractions.

Effect of sand and silt on the permanent wilting point: Significant interactive relationships were determined as seen in Fig. 4a. The permanent wilting point increased as the silt fraction decreased in the high sand fractions, whereas the permanent wilting point increased as the silt fraction increased in the low sand fractions. The permanent wilting point increased as the sand fraction decreased in the high silt fractions, whereas the permanent wilting point increased as the sand fraction increased in the low silt fractions.

Effect of clay and silt on the permanent wilting point: The increase of both clay and silt fractions increased the permanent wilting point in all cases (Fig. 4b). The clay and silt had a linear effect on the permanent wilting point.

Effect of clay and sand on the permanent wilting point: The increase of sand fraction reduced the permanent wilting point, whereas the sand fraction had no effect on the permanent wilting point in the low clay fractions (Fig. 4c). An interactive relationship between the permanent wilting point and the clay fraction was determined. The permanent wilting point increased in the high sand fractions, whereas the permanent wilting point increased as the clay fraction increased in the low sand fractions.

Sand, one of the textural fractions, was the variable that affected the field capacity and permanent wilting point at most. In the regression equations developed for the estimation of the field capacity and permanent wilting point using the multiple-linear regression models; sand, silt, clay and bulk density were used as independent variables. The 92 and 97% of the variations in the field capacity and permanent wilting point represented by the simple-regression and multiple-regression models, respectively.

These results indicate that the field capacity and permanent wilting point may be estimated with reasonable accuracy for soils where field or laboratory measurements are not available. A wide range of particle sizes and bulk density might be helpful for better estimations. In addition, salinity, organic matter content and mineral type of soils can be considered for future study for the estimation of the filed capacity and permanent wilting point.

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