Modeling cation exchange capacity and soil water holding capacity from basic soil properties

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Abstract

Cation exchange capacity (CEC) is a good indicator of soil productivity and is useful for making recommendations of phosphorus, potassium, and magnesium for soils of different textures. Soil water holding capacity (SWHC) defines the ability of a soil to hold water at a particular time of the season. This research predicted CEC and SWHC of soils using pedotransfer models developed (using Minitab 17 statistical software) from basic soil properties (Sand(S), Clay(C), soil pH, soil organic carbon (SOC)) and verify the model by comparing the relationship between measured and estimated (obtained by PTFs) CEC and SWHC in the Forest Vegetative Zone of Nigeria. For this study, a total of 105 sampling points in 35 different locations were sampled in the study areas. Three sampling points were randomly selected per location and three undisturbed samples were collected at each sampling point. The results showed success in predicting CEC and SWHC from basic soil properties. In this study, five linear regression models for predicting soil CEC and seven linear regression models for predicting SWHC from some soil physical and chemical properties were suggested. Model 5 [CEC = -13.93+2.645 pH +0.0446 C (%)+2.267 SOC (%)] was best for predicting CEC while model 12 [SWHC (%)=36.0- 0.215 S (%)+0.113 C (%)+10.36 SOC (%)] is the most acceptable model for predicting SWHC.

Keywords: Cation exchange capacity, soil water holding capacity, pedotransfer function, multiple linear regression, Nigeria.

Introduction

Cation exchange capacity (CEC) of a soil is a measurement of its ability to bind or hold exchangeable cations. In other words, it is a measure of the number of negatively-charged binding sites in soil (Rashidi and Seilsepour, 2008). The cation exchange capacity of a soil represents the total amount of exchangeable cations that a soil can retain. Cation exchange capacity helps characterize the soil type under consideration. For example, because organic matter in soil is a major source of negative electrostatic sites there is a strong correlation between CEC values, and amount of organic matter present in soil (Harada and Inoko, 1975). The CEC results provided insight into the type of soil, as well as secondary information for use in formulating a fertilizer programme. Characterization of soils' CEC is useful for making recommendations for the amounts of phosphorus, potassium, and magnesium for soils of different textures.

Soil water holding capacity (SWHC) is the amount of water retained in capillary spaces of soil after gravitational water loss into deeper layers of the soil (Senjobi and Ogunkunle, 2011). Soil water storage available for plant use is generally calculated as being between field capacity and wilting point, as water

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contents higher than, while usually plant-available, are generally not sustained for long times except under specific circumstances (Sumner, 2000). The estimation of SWHC of a soil is of great value to practical agriculture, because it provides a simple means of determining moisture contents required for soils, for good plant growth, and infiltration of water into soil which is another important dynamic flow processes in the hydrological cycle (Viji and Rajesh, 2011). Knowing the soil water storage capacity allows the irrigator to determine how much water to apply at one time and how long to wait between each irrigation (Olorunfemi, 2014). Soil water holding capacity of any soil is determined by its texture, structure, and organic matter content. Soil texture influences the water retention capabilities of soils of different locations, as soils with high clay percentage or both (high clay percentage and organic matter content) tends to have high SWHC (Senjobi and Ogunkunle, 2011). Soil texture and crop rooting depth affect total amount of water stored in the soil within the plant's rooting zone. Therefore, characterizing SWHC of different locations is about defining the ability of a soil to hold water by soil and for use by a particular crop at a particular time of the season.

Cation exchange capacity and soil water holding capacity can be measured by laboratory experiments. Despite the progress made in measuring soil properties directly, laboratory analysis of some soil physical and chemical properties is still laborious and expensive to obtain. For example, CEC is often determined using laborious and time consuming laboratory tests. Also, soil properties can be highly variable spatially and temporally and measuring these properties is time consuming and difficult, but it may be more suitable, economical and essential to derive relationships that link the basic soil properties to the functional soil properties that are more difficult to measure. Recently, indirect estimation of these functional properties from widely available or more easily measured basic soil properties like; sand (S), silt (Si), clay (C), bulk density (BD), soil organic carbon (SOC) and soil organic matter (SOM) that contribute to the functional properties using pedotransfer functions (PTFs) has received considerable attention (Wösten et al., 1995; Minasny and McBratney, 2002; Minasny et al., 2004, Amini et al., 2005). According to Martel et al. (1978), Manrique et al. (1991), and Rashidi and Seilsepour (2008), soil components known to contribute to soil CEC are clay and organic matter, and to a lesser extent, silt. Several researchers: Yuan et al. 1967 (for sandy soils in Florida); Drake and Motto 1982 (for New Jersey soils); Sahrawat 1983 (for some Philippine soils) and Bell and van Keulen 1995 (for four soils in Mexico) have attempted to predict CEC from clay and organic carbon contents, while and Rashidi and Seilsepour (2008) predicted CEC from organic carbon alone for soils in Varamin, Iran, using multiple regression. Also, Krogh et al. (2000) suggested an equation based on silt, clay, organic carbon, and pH. In most of these models, CEC is assumed to be a linear function of soil organic matter and clay content (Breeuwsma et al., 1986; McBratney et al., 2002).

This study will determine relationships linking basic soil properties to CEC and SWHC thereby providing quick and easy determination of CEC and SWHC. The knowledge of these properties and process leads to better predictions of agricultural soil water management systems. In the light of the above, objectives of this research were to predict CEC and SWHC of soils using pedotransfer models developed from basic soil properties. Then, verify the model by comparing the relationship between measured and estimated (obtained by PTF) values in the forest vegetative zone of Nigeria.

Material and Methods

Experimental site and procedure

Experimental site

The study was conducted in Ekiti State in the forest vegetative zone of Nigeria (Figure1). Ekiti State is located between Latitudes 7° 15' to 8° 5' N and Longitude 4° 45' to 5° 45' E and occupies an area of about 6, 353 km² (EKSG, 2009). The State is mainly an upland zone, rising over 250 m above sea level. The highest contour line of 540 m above sea level is found around the North Eastern limit of the state (Simon–Oke and Jegede, 2012). It lies on an area underlain by metamorphic rock and is potentially rich in mineral deposits which include granite, kaolin, columbite, channockete, iron ore, barite, aquamine, gemstone, phosphate, limestone, gold among others largely deposited in different towns and villages within the State. The State enjoys tropical climate with two distinct seasons. These are the rainy season (April – October) and dry season (November – March). The air temperature ranges between 21° and 28° with high humidity. Ekiti State has a total annual rainfall of about 1400 mm with an average of about 112 rainy days per year (Adebayo, 1993). The dominant soils in Ekiti state are Egbeda series and Iwo series (Syrnth and Montgomery, 1962). Under the FAO/UNESCO classification, they are Orthic and Plinthic Luvisols, respectively (FAO, 1998). The vegetation of Ekiti State is guinea forest with its attendant climate, flora and fauna (EKSG, 2009).

Figure 1. Location of the study area

Experimental procedure

Soil sampling and field experiments were carried out across 35 different locations (communities) in Ekiti State. Undisturbed soil samples from the topsoil (Horizon A) were collected from each experimental site using stainless steel cylindrical cores. Soil samples were collected in depths of 0 to 30 cm. Three sampling points were randomly selected per location and three undisturbed samples were collected at each sampling point. In general, 105 soil samples were taken randomly at the different locations in Ekiti State. Soil samples collected were packed in plastic bags, and transferred to the laboratory. The samples were allowed to dry in the open air until reaching friability.

Measurements

Physico-chemical characterization of soils

Chemical characterization of the collected soil samples include the analysis of SOM, SOC, CEC at pH of 7.0, base saturation, Al^{3+} saturation and soil pH. Physical characterization consisted of particle size analysis, SWHC determination. The organic carbon was determined using Walkley - Black wet oxidation procedure and soil organic matter content was determined from organic carbon (Nelson and Sommers, 1996). The cation exchange capacity (CEC) at pH 7.0 was determined following the procedure compiled and described by Reeuwijk (2002). The exchangeable potassium (K^+) and sodium (Na^+) was extracted with HCl solution and their levels determined by flame photometry (Vogelmann et al., 2010) and exchangeable magnesium (Mg^{2+}) and calcium (Ca^{2+}) by atomic absorption spectrophotometer (Senjobi and Ogunkunle, 2010). Soil pH was determined in distilled water using the pH meter with water ratio of 1:2. Soil particle sizes were determined using the hydrometer method described in Agbede and Ojeniyi (2009). Soil water holding capacity was determined following the method described by Ibitoye (2006).

Statistical analysis

Soil properties were subjected to statistical analysis to determine the mean, standard deviation, coefficient of variation among soil samples from different locations. Each soil property was compared using Pearson correlation coefficient at 1 and 5% significant levels and the existence of inter-relationships between data set was tested by linear correlation using Minitab 17 statistical software. To predict the cation exchange capacity (CEC) of soil, pedotransfer (PTF) functions, which are multiple regression equations, among soil properties were obtained using the Minitab 17 statistical software. A paired samples t-test and the mean difference confidence interval approach were used to compare predicted and measured values of soil CEC and SWHC. Descriptive statistics such as minimum and maximum value, arithmetic mean value, standard deviation (SD), and coefficient of variation (CV) were calculated to help in providing explanations and assessing dispersion of the variables. Measure of Dispersion tells us about the variation of the data set.

Statistics such as Correlation Coefficient (R), Root Mean Square Error (RMSE), Mean Absolute Error (MAE), and Relative Error (RE) were calculated using equation (1), (2), (3), and (4) respectively, where n represents the number of instances presented to the model and O_i and P_i represents measured and predicted, and O_{ave} and P_{ave} represents mean values of measured and predicted respectively.

$$R = \left[\frac{\sum_{i=1}^{n}(O_i - O_{ave})(P_i - P_{ave})}{\sqrt{\sum_{i=1}^{n}(O_i - O_{ave})^2 (P_i - P_{ave})^2}}\right] \quad (1)$$

$$RMSE = \left[\frac{\sum_{i=1}^{n}(P_i - O_i)^2}{n}\right]^{1/2} \quad (2)$$

$$MAE = \sum_{i=1}^{n}[|P_i - O_i|/n] \quad (3)$$

$$RE = (MAE/O_{ave})100 \quad (4)$$

Results and Discussion

Physical and chemical properties of sampled soils

Descriptive statistics of some physical and chemical properties of the soils used in this study were given in Table 1. Cation exchange capacity of all 35 sampled soils ranged from 3.43 $cmol_c kg^{-1}$ to 11.97 $cmol_c kg^{-1}$ with an average value of 6.53 $cmol_c kg^{-1}$ ± 2.01. Cation exchange capacity values showed that the distribution is positively and moderately skewed with a skewness coefficient of 0.78 while values of the coefficient of kurtosis of 0.16 suggested a platykurtic behavior in their distribution. The soil water holding capacity (SWHC) ranged from 29.27% to 71.83% for all soil samples in the 35 locations with an average value of 45 %, standard deviation of 3.05 and coefficient of variation of 70 %. The skewness coefficient (1.28) of the SWHC of the sampled locations reveals a distribution that is positive and highly skewed while the kurtosis coefficient (2.57) showed that the distribution is platykurtic. Skewness and kurtosis reveal the direction of variation of the data set. It also informs about the normality of the data set.

Table 1. Descriptive statistics of physical and chemical properties of sampled soils

Statistics/Soil Properties	Sand (%)	Silt (%)	Clay (%)	Soil pH	SOC (%)	SOM (%)	SWHC (%)	CEC (cmol+kg^{-1})
Minimum	24.00	4.00	20.00	4.95	0.88	1.52	29.27	3.43
Maximum	64.00	32.00	56.00	6.36	2.36	4.07	71.83	11.97
Arithmetic Mean	44.57	21.37	34.06	5.95	1.42	2.46	45.00	6.53
Standard Deviation	9.85	6.23	9.54	0.32	0.38	0.66	8.53	2.01
Coeff. of Variation	0.22	0.29	0.28	0.05	0.27	0.27	18.96	0.31
Skewness	-0.53	-0.73	0.47	-0.65	0.72	0.65	0.26	0.77
Kurtosis	-0.31	0.51	-0.70	-0.23	0.06	-0.06	1.50	0.16

Relations between CEC, SWHC, and some soil properties

Cation exchange capacity showed positive correlation with soil pH (r = 0.441[**]), SOC (r = 0.580[**]), SOM (r = 0.572[**]), SWHC (r = 0.580[**]), and clay content (r = 0.356 [*]) at $p \leq 0.01$ and $p \leq 0.05$ respectively amongst all the soil samples in the 35 experimental locations (Table 2). It was observed that soils with high organic matter content and clay particles demonstrated high CEC values which is due to the fact that the cation-exchange capacity (CEC) of soils is mainly due to clay minerals and soil organic matter (Martel et al. 1978; Manrique et al. 1991; Harada and Inoko, 1975) and silt to a lesser extent (Rashidi and Seilsepour, 2008). Organic matter in soil is a major source of negative electrostatic sites; therefore there is a strong correlation between CEC value and amount of organic matter present in the soil. The research findings were also in agreement with the works of Bayer and Bertol (1999); Vogelmann et al., (2010) and Fasinmirin and Olorunfemi (2012) who reported that soil samples with higher values of CEC were found to have high levels of organic matter and pH. Also in any given soil, the number of exchange sites is dependent on the soil pH; type, size and amount of clay; and amount and source of the organic material (Kamprath and Welch 1962; Miller 1970; Parfitt et al. 1995; Rashidi and Seilsepour, 2008). Soil water holding capacity correlated positively with clay content (r = 0.539, $p \leq 0.01$) and negatively with sand content (r = - 0.517, $p \leq 0.01$).

Results of the correlation analysis between SWHC (%) and SOM (%) revealed a significant and positive relationship (r = 0.584, N = 35, p ≤ 0 .01). Senjobi and Ogunkunle (2011) reported that soils having high proportion of sands are associated with low SWHC. The result also shows that if clay and organic matter contents increase, water holding capacity of the soil also increases (FAO, 2005). This observation correlated with the findings of Senjobi and Ogunkunle (2011) who further stated that water holding capacity of soils increase with increase in clay content of soils in their study to assess the extent to which different land use types influences land degradation and productivity in Ogun State, Nigeria. SWHC of the soils resulted from fine texture nature of the soils.

Table 2. Pearson correlations coefficient (r) among various soil properties

	pH	Sand	Silt	Clay	SOC	SOM	SWHC	CEC
pH	1							
Sand	.088 ns	1						
Silt	.065 ns	-.366*	1					
Clay	-.134 ns	-.794**	-.275 ns	1				
SOC	.128ns	-.363*	-.140 ns	.467 **	1			
SOM	.139 ns	-.339*	-.137 ns	.440**	.993**	1		
WHC	.152 ns	-.517**	-.008 ns	.539**	.610**	.584**	1	
CEC	.441**	-.281 ns	-.101 ns	.356 *	.580**	.572**	.569**	1

ns, not significant.
**Correlation is significant at the 0.01 level, *Correlation is significant at the 0.05 level

Prediction of soil cation exchange capacity (CEC) using pedotransfer models

Pedotransfer models to predict CEC value of soils were developed regarding the results of correlation analysis. The following models for CEC were obtained from multiple regressions on data (Model 1-5) The pedotransfer models, which were developed using some soil physical properties, to predict cation exchange capacity (CEC) were statistically significant at 1% probability level.

1) CEC = 2.17 + 3.072 SOC (%)
2) CEC = 1.77 + 0.0230 C (%) + 2.802 SOC (%)
3) CEC = -11.62 + 2.379 pH + 2.819 SOC (%)
4) CEC = -15.37 + 3.173 pH + 0.0890 C (%)
5) CEC = -13.93 + 2.645 pH + 0.0446 C (%) + 2.267 SOC (%)

Model 5 was the best model for predicting CEC with R = 0.711, RMSE = 1.39, MAE = 1.16 and RE = 17.77 (Table 3). Table 4 shows the result of Paired Samples Test used to compare the measured and predicted CEC values. Using an alpha level of 0.05, a dependent-samples t test was conducted to evaluate whether CEC values determined using two methods of laboratory test and pedotransfer function differed significantly. The results indicated that the CEC values determined using two methods of laboratory test (M = 6.53, SD = 2.01) was not significantly different from the CEC values predicted using the second method (M = 6.53, SD = 1.43), with t (34) = 2.83, p = 1.00

The 95% confidence interval for the mean difference between the two methods of determination was -0.48 to 0.48. Comparison of observed versus predicted values of CEC obtained from the models (1 - 5) were depicted in Figure 2 that indicates good match as a 1.0:1.0 scale and 45-degree angle with vertical.

Table 3. Summary of statistics of various models of soil cation exchange capacity (CEC)

	Statistics Parameters			
Models	R	RMSE	MAE	RE
1	0.580	1.61	1.28	19.54
2	0.588	1.60	1.23	18.79
3	0.687	1.44	1.22	18.74
4	0.608	1.57	1.29	19.72
5	0.711	1.39	1.16	17.77

R: Correlation Coefficient; RMSE: Root Mean Square Error; MAE: Mean Absolute Error; RE: Relative Error.
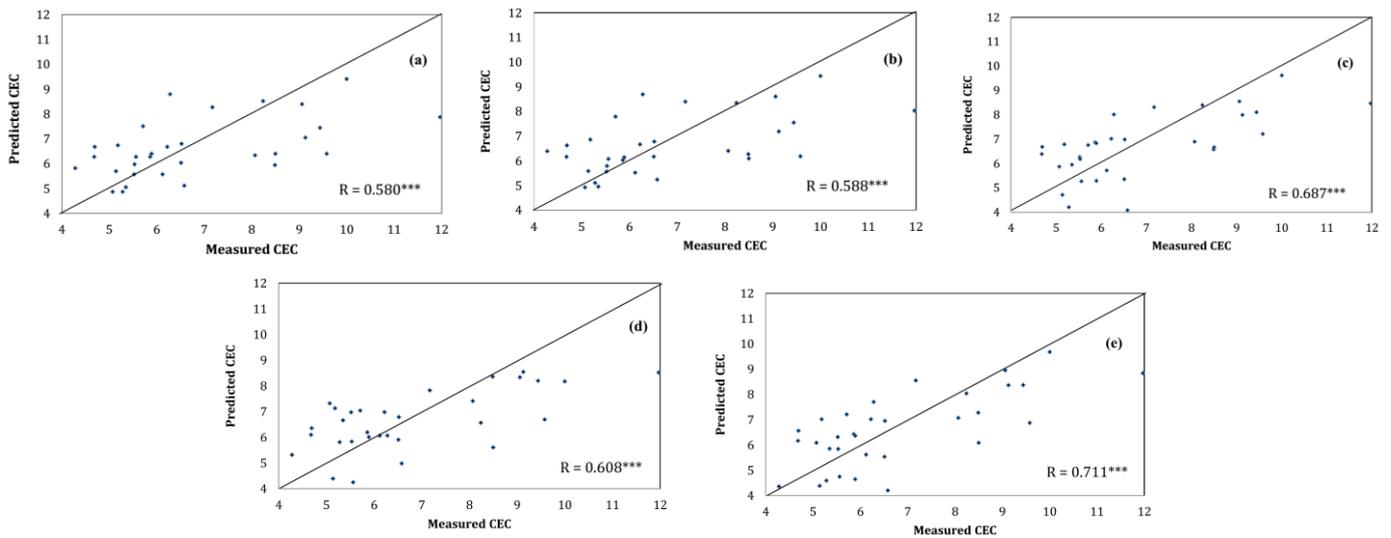
Figure 2. Comparison of measured CEC and predicted CEC for (a) model 1, (b) model 2, (c) model 3, (d) model 4, (e) model 5 with the line of equality (1.0: 1.0) (***Significant at the 0.001 level).

Table 4. Paired Samples Test analyses on comparing soil CEC determination methods

| | | Paired differences | | | | | | | Sig. |
| | | Mean | SD. | SEM | 95% confidence interval of the difference | | t | df | (2-tailed) |
					Lower	Upper			
Model No. 1	Measured CEC - Predicted CEC	.00	1.64	.27662	-.56215	.56215	.000	34	1.000
Model No. 2	Measured CEC - Predicted CEC	.00	1.62	.27467	-.55819	.55819	.000	34	1.000
Model No. 3	Measured CEC - Predicted CEC	.00	1.46	.24646	-.50087	.50087	.000	34	1.000
Model No. 4	Measured CEC - Predicted CEC	.00	1.59	.26944	-.54758	.54758	.000	34	1.000
Model No. 5	Measured CEC - Predicted CEC	.00	1.41	.23853	-.48475	.48475	.000	34	1.000

SD; Standard Deviation, SEM; Standard Error of the Mean

Prediction of soil water holding capacity (SWHC) using Pedotransfer models

Pedotransfer models to predict SWHC values of soils were developed regarding the results of correlation analysis (Model 6-12)

6) SWHC (%) = 64.93 - 0.447 S (%)

7) SWHC (%) = 28.57 + 0.482 C (%)

8) SWHC (%) = 25.52 + 13.72 SOC (%)

9) SWHC (%) = 43.6 - 0.207 S (%) + 0.312 C (%)

10) SWHC (%) = 42.59 - 0.294 S (%) + 10.94 SOC (%)

11) SWHC (%) = 20.46 + 0.291 C (%) + 10.30 SOC (%)

12) SWHC (%) = 36.0 - 0.215 S (%) + 0.113 C (%) + 10.36 SOC (%)

Likewise, predicted SWHC values by the models and values determined by laboratory methods were not statistically significantly different from each other. The test statistics for model 12 which is the most acceptable model was based on the mean difference between paired values of the measured and predicted SWHC (0.00) relative to the SE (Standart Error) of paired difference between sampled means (0.24). Results of the paired-samples t-test (Table 5) show that mean SWHC of the measured SWHC (M = 44.50, SD = 8.53) did not differ from predicted SWHC (M = 44.50, SD = 5.89) at the 0.05 level (t = 0.00, df = 34, n = 35, p =1.00, 95% CI for mean difference – 2.12 to 2.12). Findings therefore suggest that use of pedotransfer models could be reliable for quick assessment of soil water holding capacity and cation exchange capacity of soils with

95% confidence limit. Comparison of observed vs. predicted values of CEC obtained from the models (6 - 12) has been depicted in Figure 3 that indicates good match as a 1.0:1.0 scale and 45-degree angle with vertical.

Table 5. Summary of Statistics of Various Models of Soil water holding capacity (SWHC)

Models	Statistics Parameters			
	R	RMSE	MAE	RE
1	0.517	7.20	5.27	11.70
2	0.539	7.08	5.39	11.98
3	0.610	6.66	5.17	11.49
4	0.558	6.97	5.16	11.47
5	0.687	6.11	4.53	10.06
6	0.674	6.21	4.92	10.94
7	0.691	6.08	4.60	10.21

R: Correlation Coefficient; RMSE: Root Mean Square Error; MAE: Mean Absolute Error, RE: Relative Error

Table 6. Paired Samples Test analyses on comparing soil SWHC determination methods

		Paired Differences							
					95% confidence interval of the difference				Sig.
		Mean	SD	SEM	Lower	Upper	t	df	(2-tailed)
Model No. 1	Measured WHC - Predicted WHC	.00	7.30	1.23	-2.51	2.51	.000	34	1.000
Model No. 2	Measured WHC - Predicted WHC	.00	7.18	1.21	-2.47	2.47	.000	34	1.000
Model No. 3	Measured WHC - Predicted WHC	.00	6.76	1.14	-2.32	2.32	.000	34	1.000
Model No. 4	Measured WHC - Predicted WHC	.00	7.08	1.20	-2.43	2.43	.000	34	1.000
Model No. 5	Measured WHC - Predicted WHC	.00	6.20	1.05	-2.13	2.13	.000	34	1.000
Model No. 6	Measured WHC - Predicted WHC	.00	6.30	1.06	-2.16	2.16	.000	34	1.000
Model No. 7	Measured WHC - Predicted WHC	.00	6.17	1.04	-2.12	2.12	.000	34	1.000

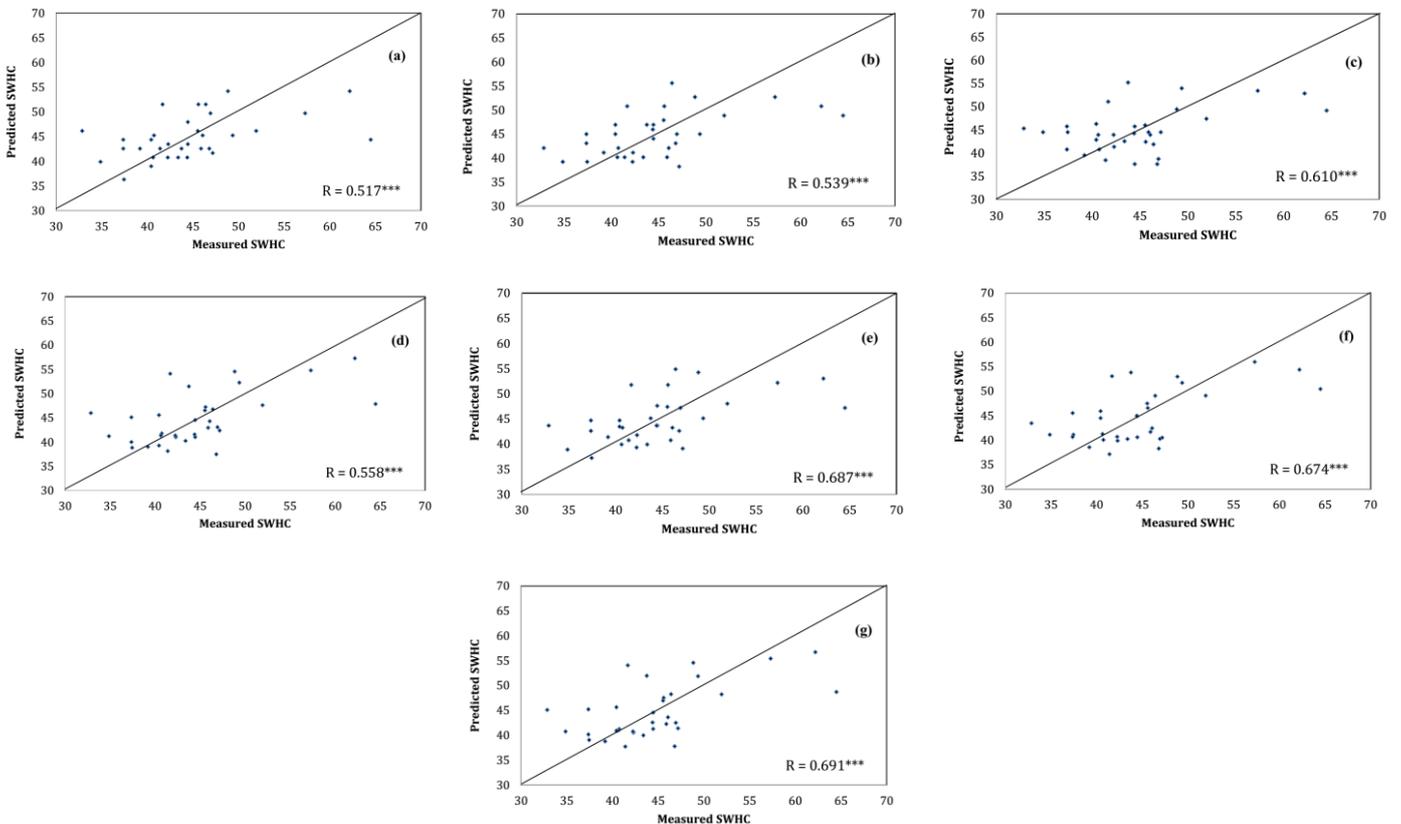SD; Standard Deviation, SEM; Standard Error of the Mean

Figure 3. Comparison of measured SWHC and predicted SWHC for (a) model 1, (b) model 2, (c) model 3, (d) model 4, (e) model 5, (f) model 6, (g) model 7 with the line of equality (1.0: 1.0) (***Significant at the 0.001 level).

Conclusion

Pedotransfer models were successfully used to predict CEC and SWHC using multiple linear regression methods from basic soil properties. The paired samples t- test results indicated that the difference between predicted and measured values of the soil CEC and SWHC were not statistically significant using an alpha level of 0.05. Therefore, by using pedotransfer models, one can derive relationships that link basic soil properties to the functional soil properties that are more expensive and difficult to measure. This will result in quicker access to more expensive soil and environmental functional properties. The knowledge of these SWHC and process leads to better predictions and management of irrigation and water management systems. Likewise, CEC is a good indicator of soil productivity and a major criterion used when making soil fertilizer recommendations. Convenience in determining these properties will result in better farm management and greater agricultural productivity.

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