ASSESSING PEDOTRANSFER FUNCTIONS TO ESTIMATE THE SOIL WATER RETENTION

VALIDAÇÃO DE FUNÇÕES DE PEDOTRANSFERÊNCIA PARA ESTIMATIVA DA RETENÇÃO DE ÁGUA NO SOLO

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ABSTRACT: Considering the importance of soil water retention for agricultural and environmental purposes, the objective of this study was to assess three pedotransfer functions (PTFs) used to estimate the soil moisture at field capacity (FC) based on soil attributes easily determined. A collection of 17 soils from the Cerrado and Pantanal biomes, including surface and subsurface horizons, was used. PTF-1 considers clay, organic matter, coarse sand, and microporosity; PTF-2 clay, total sand, and organic matter; and PTF-3 only microporosity. The estimated FC values were correlated to soil moisture values measured at different soil water potentials (0, 6, 10, 33, 100, 300, and 1500 kPa) to verify which potential corresponded to estimated FC. The data were subjected to regression analysis and Mann-Whitney rank-sum test to compare predicted and measured values and to principal component analysis (PCA). The analysis of the full dataset indicated that there was a strong correlation (R 0.84–0.91; R^2 0.71–0.82; RMSE 0.07–0.09) between estimated FC and soil water retention measured at potentials of 10 kPa and 33 kPa. FC estimated by PTF-3 correlated better with water holding capacity at 6 kPa. When the PTFs were reapplied to homogeneous soil groups (identified by PCA analysis), the correlation between predicted and measured FC was decreased.

KEYWORDS: Soil-water retention. Principal component analysis. Soil moisture.

INTRODUCTION

Water retention in soils has a crucial agronomic and environmental importance. Several phenomena depend on soil water retention, including plant growth and nutrient absorption, leaching of nutrients and pollutants, irrigation and drainage, hydrological recharge and modeling, and biochemical processes and microbial activity, among others. Water retention is determined and modeled in laboratory conditions; however, its measurement is time-consuming and costly, especially in tropical climates, where the soil properties vary widely and data are scarce (HARTEMINK, 2002; COSTA et al., 2013; BOTULA et al., 2014).

The upper limit of soil water content available to plants is known as field capacity (FC). FC has been defined as the soil water content remaining after free drainage is negligible (TOLK, 2003) and can be determined *in situ* or measured in the laboratory (VEIMEHYER; HENDRICKSON, 1949). FC is quantified in the laboratory using undisturbed soil samples saturated with distilled water and equilibrated at a soil water potential of 6, 10, or 33 kPa (REICHARDT, 1988; RUIZ et al., 2003; KLEIN et al., 2006). The remaining water content corresponds to FC. Nonetheless, a consensus about FC estimation has not been reached (REICHARDT, 1988; SOUZA; REICHARDT, 1996; SILVA et al., 2014). In Brazil, a potential of 10 kPa has been largely used for sandy and clayey soils with granular microstructure. The primary soil attributes related to FC are texture, structure, and organic matter (AULER et al., 2017). A coarse soil texture and low organic matter content result in low FC (RAWS et al., 2003; TOMASELLA et al., 2000; COSTA et al., 2013). Moreover, the size, distribution, and connectivity of pores as affected by soil structure and management strongly affect FC.

Pedotransfer functions (PTFs) have helped overcome the difficulties in estimating FC by using soil data that are easily measured and strongly associated with FC (PIDGEON, 1972; BOUMA, 1989; LOOY et al., 2017). PTFs are also available for tropical soils, including those in Brazil (MACEDO, 1991; TOMASELLA et al., 2000; REICHERT et al. 2009; COSTA et al., 2013; SANTOS et al., 2013; SOARES et al., 2014). However, much effort is still needed to accurately predict soil hydraulic properties in the tropics (MINASNY; HARTEMINK, 2011; BOTULA et al., 2014). Accurate use of PTFs depends on their thorough validation under different conditions and in this sense, Macedo et al. (2002) recommended to use their equations for sand, loamy sand, and sandy

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loam soil samples. We choose PTFs because the soil attributes used in these functions are easily determined, and physical data on Pantanal soils are limited. In this context, this study aimed to estimate FC in distinct soils samples from the Pantanal and Cerrado biomes, using three PTFs equations.

MATERIAL AND METHODS

This study was carried out using several surface and subsurface horizons of 14 soils from the Cerrado and Pantanal biomes in Brazil, totaling 69 soil samples. The soils were classified and studied during the 2012 Brazilian Meeting of Soil Classification and Correlation, Mato Grosso do Sul state, Brazil (RBCC, 2012) (Table 1). The soil attributes used in this study are shown in Table 2. The original data are available in the Field Handbook for the Soils of Pantanal and Cerrado, Mato Grosso state, Brazil (RBCC, 2012).

The volumetric soil moisture at FC was estimated using the three PTFs proposed by Macedo (1991) and Macedo et al. (2002):

$$FC = -0.01C - 0.37S + 1.36OM - 0.02CS + 0.19MC + 42.20 \quad (1)$$

$$FC = 0.05C - 0.45S + 1.80OM + 49.39 \quad (2)$$

$$FC = 0.80MC + 2.32 \quad (3)$$

where FC is field capacity (% by volume), C is clay content (%), OM is organic matter content (%), CS is coarse sand (%), and MC is microporosity (%).

The estimated FC values obtained by each PTF (1, 2, and 3) were correlated with real soil water contents determined at different potentials (0, 6, 10, 33, 100, 300, and 1500 kPa). The soil water retention curve was built according to Embrapa (2011) using a potential table and Richards's chamber.

The Shapiro-Wilk test was used to check the normality of data. The measured and estimated data were compared using Student's *t*-test (for normal data) or Mann-Whitney rank-sum test (for non-normal data). In this study, Student's *t*-test (or the Mann-Whitney rank-sum test) compared two data groups (estimated and measured data). These tests assess whether the mean estimated FC values are statistically equal to the mean measured FC values (FABIAN; OTTONI FILHO, 2000).

Principal component analysis (PCA) was performed using the software Statistica. PCA was used to identify soil groups according to the analyzed soil attributes (Table 2) and to calculate the predicted soil moisture content using the three PTFs with the remaining soil moisture at different potentials.

Table 1. Soil collection selected for this study and classified according to the Brazilian System of Soil Classification (Embrapa, 2013).

Soil nº	Soil	Horizon	Layer (cm)
1	Orthic Humiluvic Spodosol	Eko	0-6
2	Orthic Humiluvic Spodosol	Eko	6-15
3	Orthic Humiluvic Spodosol	Eko	45-81
4	Orthic Humiluvic Spodosol	Eko	81-103
5	Orthic Humiluvic Spodosol	Eko	107-132
6	Orthic Natric Planosol	SNo	0-2
7	Orthic Natric Planosol	SNo	2-8
8	Orthic Natric Planosol	SNo	25-36
9	Orthic Natric Planosol	SNo	47-75
10	Orthic Quartzarenic Neosol	RQo	0-12
11	Orthic Quartzarenic Neosol	RQo	36-58
12	Orthic Quartzarenic Neosol	RQo	58-86
13	Orthic Quartzarenic Neosol	RQo	131-145
14	Orthic Quartzarenic Neosol	RQo	0-12
15	Orthic Quartzarenic Neosol	RQo	20-40
16	Orthic Quartzarenic Neosol	RQo	40-80
17	Orthic Quartzarenic Neosol	RQo	80-125
18	Orthic Quartzarenic Neosol	RQo	0-4
19	Orthic Quartzarenic Neosol	RQo	4-30
20	Orthic Quartzarenic Neosol	RQo	30-60

21	Orthic Quartzarenic Neosol	RQo	60-103
22	Orthic Quartzarenic Neosol	RQo	0-5
23	Orthic Quartzarenic Neosol	RQo	
24	Orthic Quartzarenic Neosol	RQo	56-78
25	Orthic Quartzarenic Neosol	RQo	88-107
26	Orthic Quartzarenic Neosol	RQo	107-128
27	Orthic Haplic Chernosol	MXo	0-10
28	Orthic Haplic Chernosol	MXo	10-29
29	Orthic Haplic Chernosol	MXo	29-50
30	Orthic Haplic Chernosol	MXo	50-72
31	Eutrophic Regolitic Neosol	RRe	0-10
32	Eutrophic Regolitic Neosol	RRe	
33	Eutrophic Regolitic Neosol	RRe	28-63
34	Eutrophic Regolitic Neosol	RRe	91-125
35	Eutrophic Haplic Gleisol	GXve	0-4
36	Eutrophic Haplic Gleisol	GXve	
37	Eutrophic Haplic Gleisol	GXve	18-45
38	Eutrophic Haplic Gleisol	GXve	64-91
39	Orthic Haplic Vertisol	VXo	0-4
40	Orthic Haplic Vertisol	VXo	
41	Orthic Haplic Vertisol	VXo	16-26
42	Orthic Haplic Vertisol	VXo	34-57
43	Saprolitic Carbonatic Haplic Cambisol	CXk	0-5
44	Saprolitic Carbonatic Haplic Cambisol	CXk	
45	Saprolitic Carbonatic Haplic Cambisol	CXk	30-55
46	Orthic Quartzarenic Neosol	RQo	0-5
47	Orthic Quartzarenic Neosol	RQo	9-19
48	Orthic Quartzarenic Neosol	RQo	19-53
49	Orthic Quartzarenic Neosol	RQo	53-80
50	Eutrophic Haplic Planosol	SXe	0-4
51	Eutrophic Haplic Planosol	SXe	30-45
52	Eutrophic Haplic Planosol	SXe	45-87
53	Petrocalcic Rendzic Chernosol	MDlk	0-8
54	Petrocalcic Rendzic Chernosol	MDlk	8-24
55	Petrocalcic Rendzic Chernosol	MDlk	24-41
56	Petrocalcic Rendzic Chernosol	MDlk	41-61
57	Tipic Eutrophic Red Nitosol	Nve	61-72
58	Tipic Eutrophic Red Nitosol	Nve	10-23
59	Tipic Eutrophic Red Nitosol	Nve	23-39
60	Tipic Eutrophic Red Nitosol	Nve	39-59
61	Dystroferric Red Latosol	LVdf	0-7
62	Dystroferric Red Latosol	LVdf	07-14
63	Dystroferric Red Latosol	LVdf	29-47
64	Dystroferric Red Latosol	LVdf	47-70
65	Quartzarenic Neosol	RQ	0-12
66	Quartzarenic Neosol	RQ	12-27
67	Quartzarenic Neosol	RQ	27-47
68	Quartzarenic Neosol	RQ	47-73
69	Quartzarenic Neosol	RQ	73-118

Table 2. Soil attributes selected to estimate the field capacity (FC).

Nº	Clay	Sand	Organic matter	Coarse sand	Microporosity
	---%*---				
1	4	81	1.3	17	36
2	4	90	0.8	23	37
3	4	94	0.1	21	26
4	6	91	0.4	23	21
5	14	82	0.1	18	25
6	6	58	10.1	19	50

7	10	60	2.5	20	48
8	6	72	0.1	21	28
9	35	38	0.2	10	38
10	4	93	1.0	29	21
11	4	92	0.2	28	20
12	4	95	0.1	30	20
13	4	95	0.0	30	24
14	4	93	0.8	30	24
15	4	94	0.2	29	22
16	4	94	0.2	29	22
17	4	95	0.1	29	23
18	6	63	3.8	12	30
19	8	82	1.0	16	27
20	10	84	0.5	17	27
21	8	86	0.3	20	32
22	4	91	1.2	13	35
23	4	93	0.5	13	32
24	4	95	0.0	14	26
25	6	88	0.1	12	28
26	6	88	0.0	11	28
27	25	57	2.2	37	33
28	27	56	1.8	37	32
29	25	58	1.0	38	29
30	25	54	0.5	35	29
31	10	73	2.1	63	20
32	10	76	0.8	64	15
33	10	69	0.5	61	14
34	10	80	0.2	63	17
35	38	23	5.7	14	35
36	36	34	2.8	21	28
37	21	50	0.5	32	33
38	23	45	0.2	30	29
39	32	32	5.9	22	31
40	34	39	3.5	21	35
41	40	32	1.9	20	31
42	44	33	0.8	21	37
43	47	11	8.8	7	40
44	55	11	4.1	6	38
45	64	12	1.2	6	38
46	4	84	1.3	13	32
47	4	91	0.3	14	23
48	4	93	0.1	14	21
49	4	92	0.1	16	22
50	12	43	4.1	4	31
51	38	39	0.4	6	29
52	36	44	0.3	8	29
53	17	54	8.5	19	51
54	21	53	6.9	15	45
55	19	58	5.2	19	43
56	11	73	4.4	33	45
57	58	17	3.4	8	31
58	60	16	2.6	9	35
59	66	14	1.9	7	39
60	74	12	1.5	6	41
61	61	16	4.3	7	31
62	63	16	3.6	8	35
63	66	19	2.2	8	40
64	66	20	1.8	8	42
65	10	88	1.0	41	18
66	10	89	0.4	40	15

67	12	86	0.3	34	13
68	12	85	0.3	32	14
69	14	85	0.2	32	13
Average	22	63	1.8	22	30
Median	11	72	0.8	20	29
Standard deviation	21	30	2.3	14	9

* % unit was used to respect the original equations (1, 2 and 3). According to International System of Units (SI), for total sand, clay, coarse sand and organic matter 1 % = 10 g kg^{-1} and for microporosity 1 % = (cm^3 cm^{-3}).100

RESULTS AND DISCUSSION

PCA identified four soil groups (Figure 1). The soil groups were classified by texture. The first group included soils with a clay content ranging from 6.2% to 35.2%: surface and subsurface samples from Planosols and Chernosols and subsurface samples from Gleisols. The second group included clay soils (clay content ranging from 35.2% to 74.1%): surface and subsurface samples from Gleisols, Vertisols, Cambisols, Nitosols, and Latosols, and subsurface samples from Planosols. The third and fourth groups included sandy soils (clay content of less than 15.0%). The third group was formed by surface and subsurface samples from Spodosols and Orthic Quartzarenic Neosols, and by subsurface samples (depth of 25 to 36 cm) from Orthic Natric Planosols. The fourth group comprised soils with the highest coarse sand content: surface and subsurface samples from Orthic Quartzarenic Neosols, Quartzarenic Neosols, Eutrophic Regolithic Neosol and one subsurface sample (depth of 45 to 81 cm) from Orthic Humiluvic Spodosol.

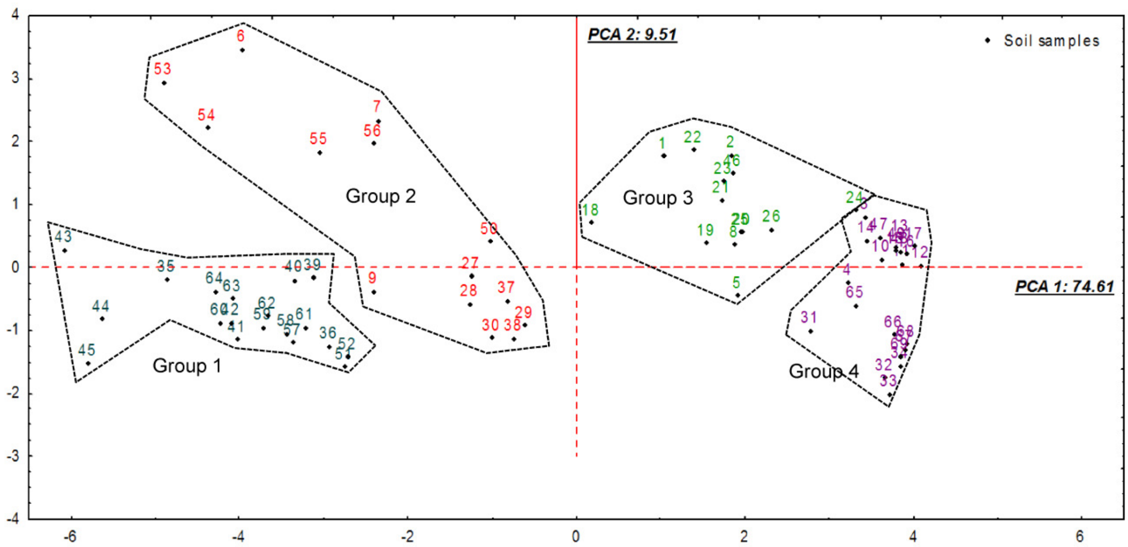

Figure 1. Principal component analysis (PCA 1 and PCA 2) of the studied soils. The dots and numbers represent the soil order. Group 1: 6, 7, 9, 27, 28, 29, 30, 37, 38, 50, 53, 54, 55, and 56. Group 2: 9, 35, 36, 39, 40, 41, 42, 43, 44, 45, 51, 52, 57, 58, 59, 60, 61, 62, 63, and 64. Group 3: 1, 2, 4, 5, 8, 19, 20, 21, 22, 23, 25, 26, and 46. Group 4: 3, 10, 11, 12, 13, 14, 15, 16, 17, 24, 31, 32, 33, 34, 47, 48, 49, 65, 66, 67, 68, and 69.

PCA indicated that FC estimated by PF-1 was closer to soil moisture at 10 KPa and 33 KPa compared with FC estimated by PF-2 and PF-3 (Figure 2). In addition, the results of the Mann-Whitney rank-sum test revealed that there was no statistically significant difference between the FC estimated by PTFs 1, 2, and 3, and the soil moisture remaining at 10 KPa and 33 KPa (except for PTF-1 at 33 KPa). Moreover, there was a negative correlation between sand content (total and coarse) and soil water retention. The clay content was more related to the remaining soil moisture at higher potentials.

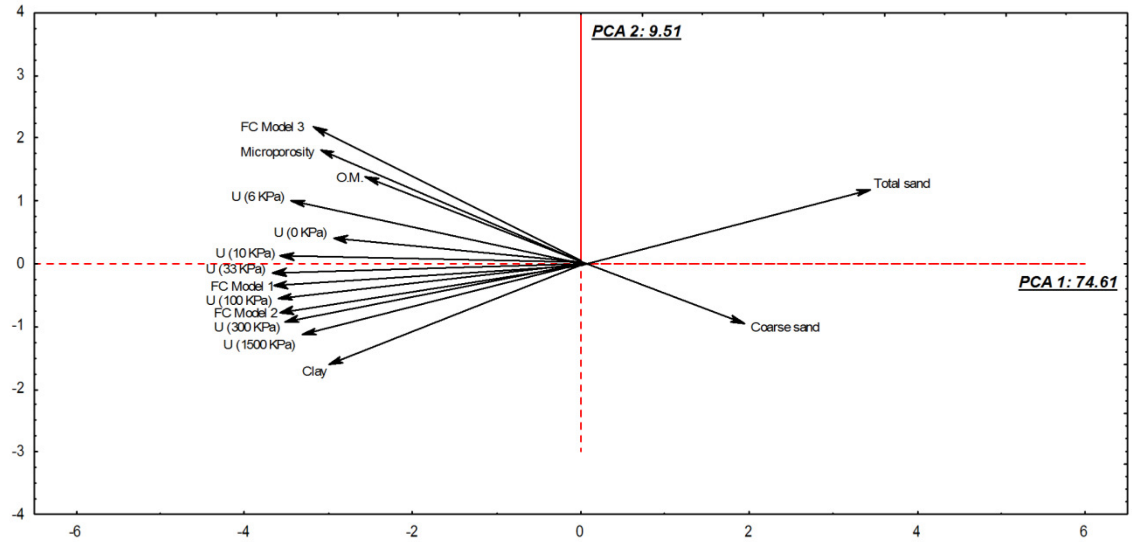

Figure 2. Principal component analysis (PCA 1 and PCA 2) of the soil attributes and FC estimated by PTFs 1, 2, and 3 (the order is represented by the arrows).

Table 2. Mann-Whitney rank-sum test (p-value) comparing field capacity (FC) estimated by PTFs 1, 2, and 3 (MACEDO, 1991) and the soil moisture remaining at different potentials.

PF	Applied tension (KPa)						
	0	6	10	33	100	300	1.500
1	< 0.001*	0.003*	0.950^{ns}	0.026*	< 0.001*	< 0.001*	< 0.001*
2	< 0.001*	0.003*	0.392^{ns}	0.204^{ns}	< 0.001*	< 0.001*	< 0.001*
3	< 0.001*	< 0.001*	0.714^{ns}	0.134^{ns}	0.002*	< 0.001*	< 0.001*

*statistically significant difference: the difference in the median values between the two groups is higher than would be expected by chance; ns, no statistically significant difference: the difference in the median values between the two groups may be due to random sampling variability.

FC values estimated by PTFs 1, 2, and 3 and correlated with the soil water contents measured at different potentials (kPa) are shown in Figures 3, 4, and 5, respectively. The best fit (1:1 regression line) for all PTFs was obtained for estimated FC values and soil moisture at 10 kPa. A potential of 10 kPa or 33 kPa is commonly used to determine the water holding capacity of soils (upper limit of the water content available to plants). Nonetheless, there is not a consensus about the optimal potential to be applied to different soils. For instance, soil water retention at 10 kPa or 33 kPa did not represent the upper water limit available under field conditions for cohesive horizons from Yellow Latosol (AGUIAR NETTO et al., 1999).

The PTFs proposed by Macedo (1991) were obtained for sandy surface horizons from Argisols. In this study, the mean and median concentration of sand in the soil collection used was 63% and 72%, respectively (Table 2). These results may help explain the suitability of all tested PTFs to estimate FC (Figures 3, 4, and 5). The tested PFs were also appropriately correlated with the determined FC *in situ* (FABIAN; OTTONI FILHO, 2000).

The predicted FC values allowed estimating the soil water content remaining at the applied potentials. All PTFs were significant (F test) with R^2 ranging from 0.42 to 0.83, indicating that the water content remaining at different tensions (from 0 to 1500 KPa) was associated with FC values estimated using the three PTFs. Ghanbarian-Alavijeh and Millán (2010) also found that the water contents at different matric potentials were linearly correlated with each other.

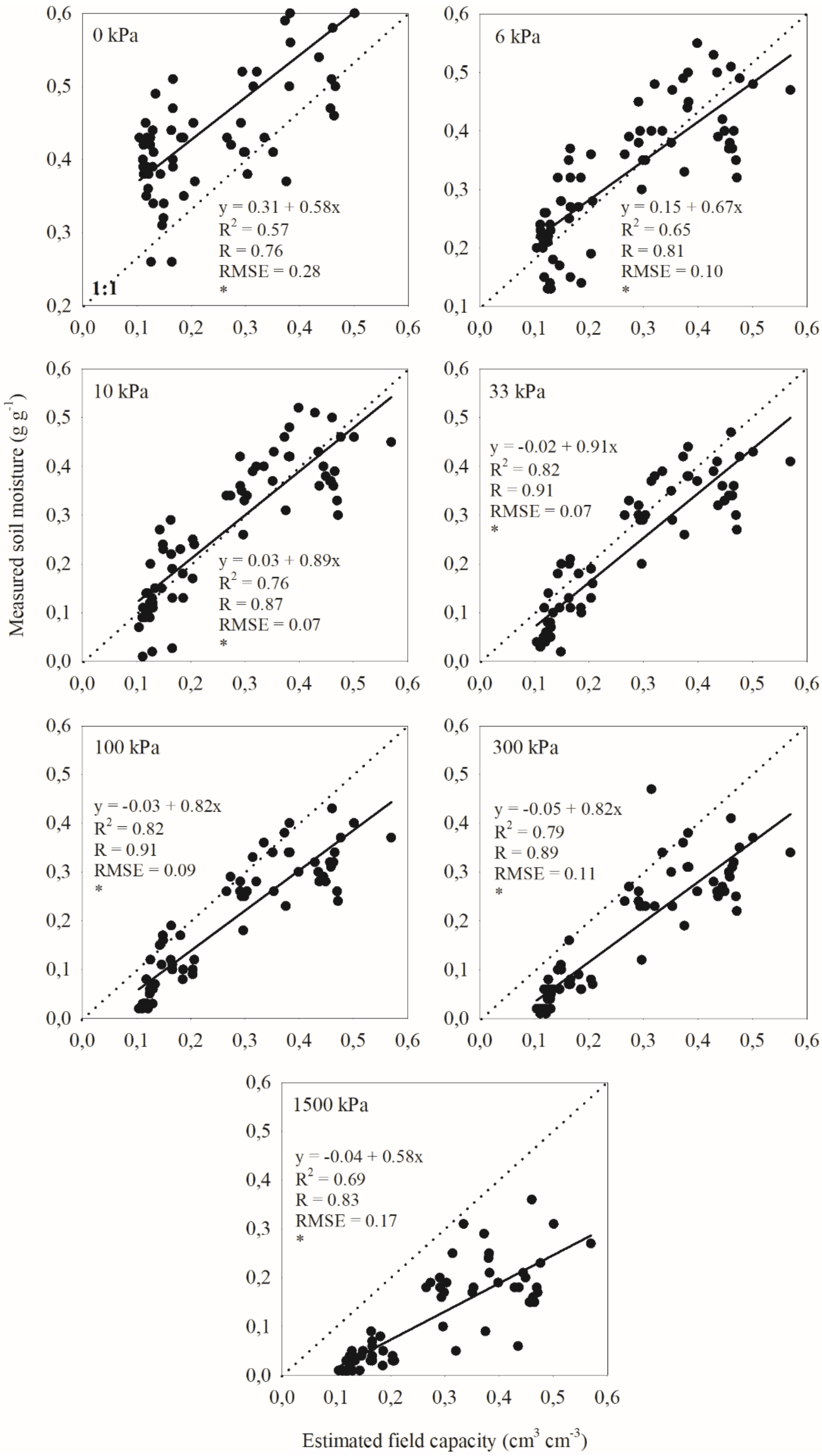

Figure 3. Linear regression between field capacity (FC) estimated by PTF-1 and soil moisture measured at different tensions (0, 6, 10, 33, 100, 300, and 1500 KPa). The dotted line represents the 1:1 regression line. *p<0.001 (F test).

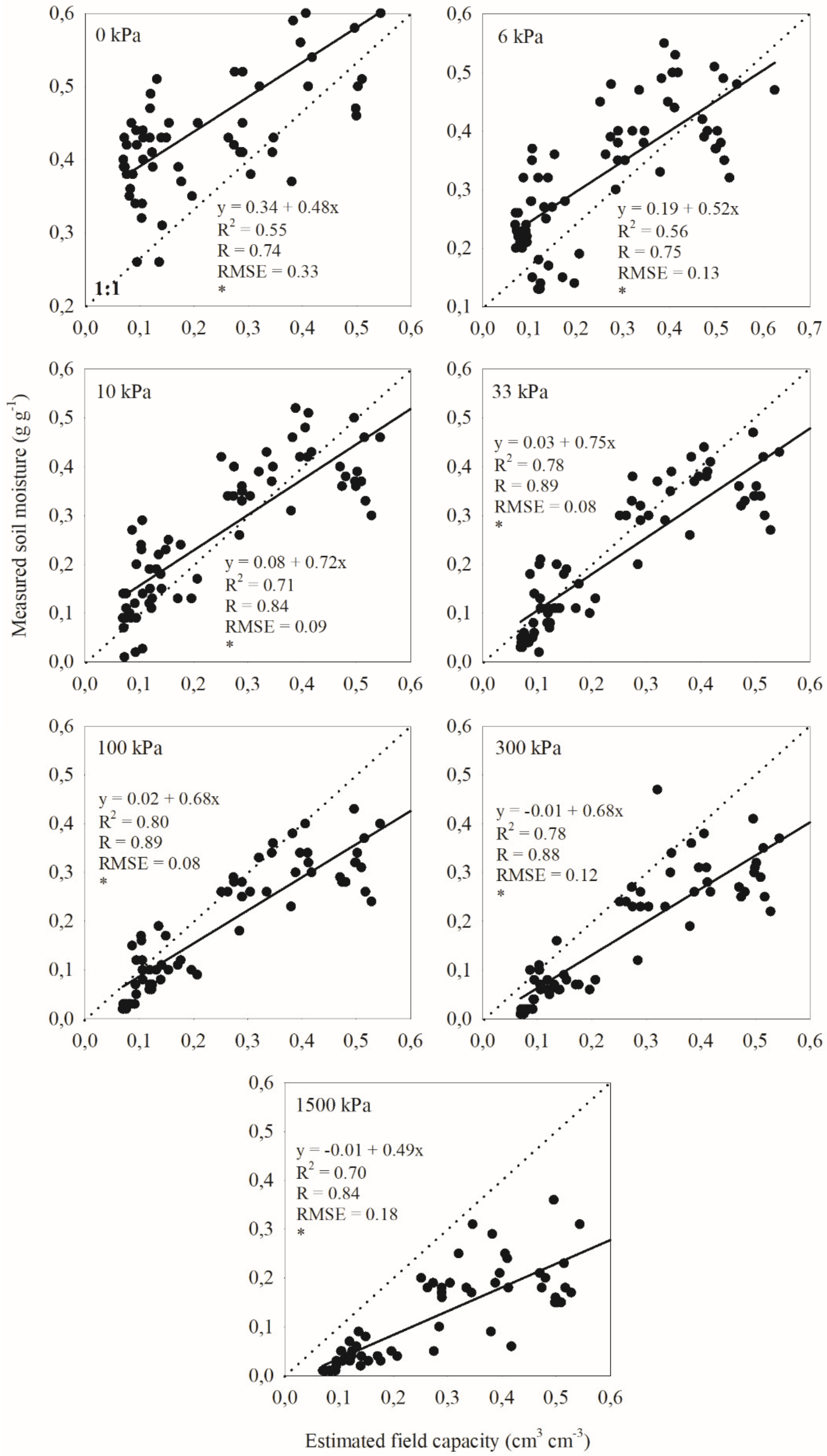

Figure 4. Linear regression between field capacity (FC) estimated using PTF-2 and soil moisture quantified at different tensions: 0, 6, 10, 33, 100, 300, and 1500(KPa). The dotted line represents the 1:1 regression line. *p<0.001 (F test).

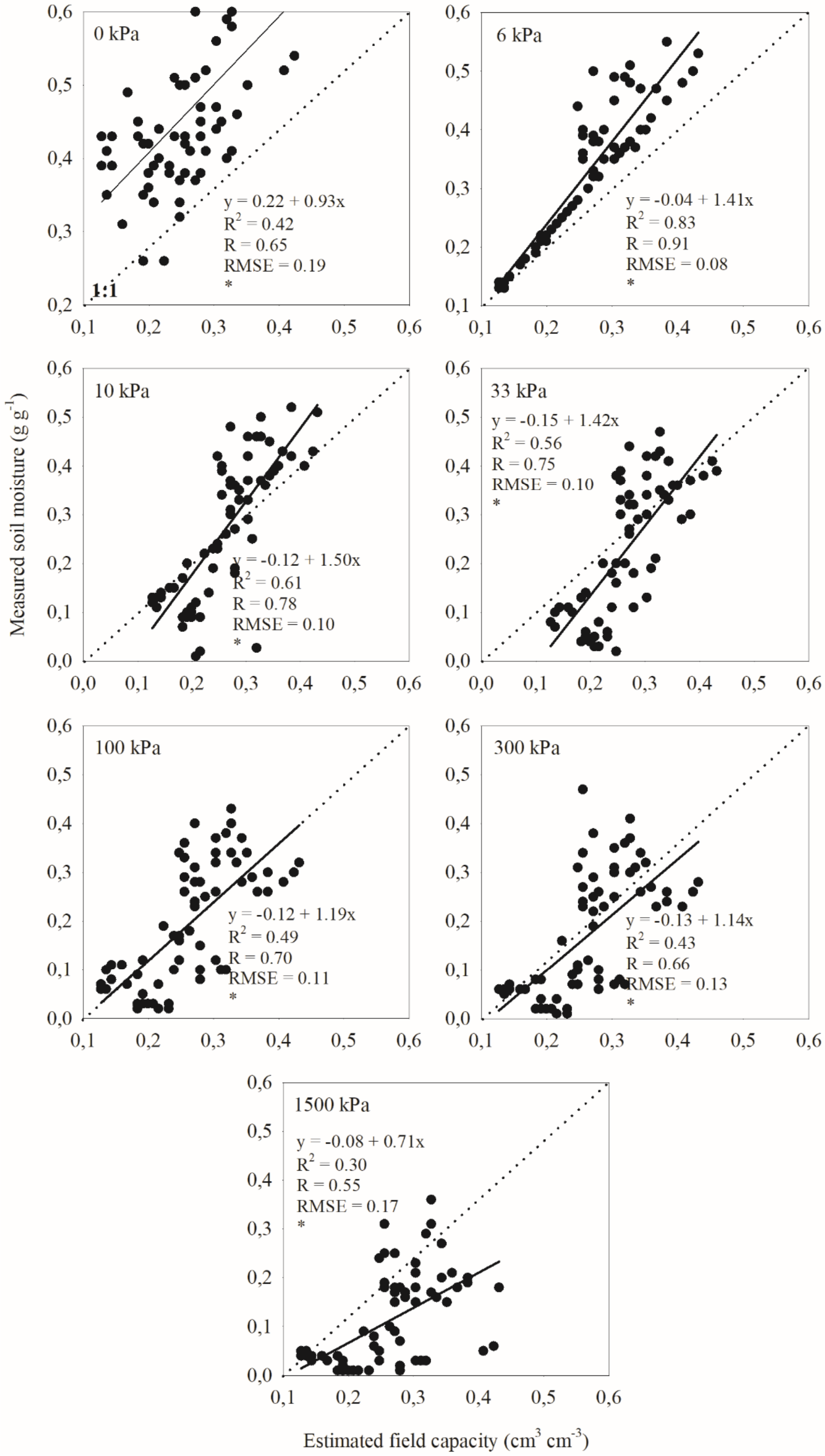

Figure 5. Linear regression between field capacity (FC) estimated using PF3 and soil moisture measured at different tensions (KPa): 0, 6, 10, 33, 100, 300, and 1500. The dotted line represents the 1:1 regression line. *p<0.001 (F test).

After four soil groups were identified by PCA, PTFs 1, 2, and 3 were reapplied in each soil group to estimate FC at 10 KPa and 33 KPa (Table 3). In group 1, the three PTFs accurately predicted FC at 33 KPa. In group 2, PTF-1 accurately predicted FC at 10 KPa. In group 3, PTF-1 accurately estimated FC at 33 KPa. In group 4, PTFs 1 and 2 appropriately estimated FC at 10 KPa. PTFs 1 and 2 presented a larger variation than PTF-3 (equations 1 to 3). PTF-3 predicted only microporosity and was suitable for only one condition (group 1 soils at 10 KPa).

Table 3. Mann-Whitney rank-sum test (p-value) comparing field capacity (FC) estimated by PTFs 1, 2, and 3 (Macedo, 1991) and the soil moisture content remaining at 10 KPa and 33 KPa for each soil group identified by PCA.

PF	Tension (kPa)							
	10	33	10	33	10	33	10	33
	Group 1		Group 2		Group 3		Group 4	
1	0.03*	0.77^{ns}	0.133^{ns}	0.002*	0.002*	0.47^{ns}	0.15^{ns}	< 0.001*
2	0.009*	0.48^{ns}	0.007*	<0.001*	< 0.001*	0.04*	0.83^{ns}	0.002*
3	0.05*	0.63^{ns}	<0.001*	<0.001*	0.02*	< 0.001*	< 0.001*	< 0.001*

* statistically significant difference: the difference in the median values between the two groups was higher than would be expected by chance; ns, no statistically significant difference: the difference in the median values between the two groups may be due to random sampling variability.

CONCLUSIONS

Considering the full dataset, a good 1:1 ratio between estimated field capacity and observed soil water retention at 10 kPa was obtained.

Predicted field capacity was statistically similar to measured values. Principal component analysis identified four different soil groups based on texture.

After reapplying the pedotransfer functions to each soil group, the difference between predicted and measured values increased.

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RESUMO: Considerando a importância da retenção de água no solo para fins agronômicos e ambientais, objetivou-se com este trabalho avaliar três funções de pedotransferência (FP) para estimativa da capacidade de campo (CC) com base em atributos de solo facilmente determinados. Uma coleção de 17 solos dos biomas Cerrado e Pantanal, incluindo amostras superficiais e subsuperficiais, foram utilizadas. FP 1 considera o conteúdo de argila, matéria orgânica, areia grossa e microporosidade. FP 2 considera argila, areia total e matéria orgânica. A FP 3 leva em consideração apenas microporosidade. Os valores estimados de CC foram correlacionados aos valores de umidade obtidos em diferentes potenciais (0, 6, 10, 33, 100, 300, and 1500 kPa) com o intuito de verificar qual potencial corresponde à CC estimada. Os dados foram submetidos à análise de regressão, ao teste Mann-Whitney rank-sum para comparar valores medidos e estimados e realizada análise de componentes principais (PCA). Considerando todo o conjunto de dados, foi obtida uma forte correlação (R 0.84–0.91; R^2 0.71–0.82; RMSE 0.07–0.09) entre CC estimada e a umidade do solo obtida nos potenciais de 10 kPa e 33 kPa. A CC estimada pela FP 3 correlacionou melhor com a retenção de água no potencial de 6 kPa. Quando as FP's foram reaplicadas em grupos de solos homogêneos (identificados pela PCA), a correlação entre valores estimados e medidos diminuiu.

PALAVRAS-CHAVE: Retenção de água no solo. Análise de componentes principais. Umidade do solo.

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