e-ISSN 1983-4063 - *www.agro.ufg.br/pat* - Pesq. Agropec. Trop., Goiânia, v. 54, e78125, 2024

Research Article

How can the inflection point of the water retention curve and the soil physical attributes be used to forecast field capacity?[1]

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ABSTRACT

Agricultural productivity is closely related to soil physical attributes, specifically those that affect the soil-water relationship, as the soil serves as the main water reservoir for plants. This research aimed to determine the field capacity for different soils, using equations based on the water retention curve. The database used included 150 soil profiles from studies published by other authors encompassing information related to textural classification, soil bulk density, particle density and soil water retention. The inflection point for each soil profile and the corresponding matrix potential were generated. Multiple correlations were established between volumetric moisture at field capacity and clay, silt and sand contents. The calculated inflection point can be an estimator of field capacity, what may facilitate and speed up the calculation of water availability.

KEYWORDS: Irrigation management, soil moisture, soil water retention curve.

RESUMO

Como utilizar o ponto de inflexão da curva de retenção de água e os atributos físicos do solo para previsão da capacidade de campo?

A produtividade agrícola está intimamente relacionada aos atributos físicos do solo, em especial àqueles que afetam a relação solo-água, uma vez que o solo se constitui no principal reservatório hídrico para as plantas. Objetivou-se determinar a capacidade de campo para diferentes solos, a partir de equações baseadas na curva de retenção de umidade. Foi utilizado um banco de dados com 150 perfis obtidos de trabalhos publicados por outros autores, com informações sobre classificação textural, densidade aparente do solo, densidade de partícula e retenção de água no solo. Foi gerado, para cada perfil, o ponto de inflexão, assim como o potencial matricial correspondente ao seu valor. Foram estabelecidas correlações múltiplas entre a umidade volumétrica na capacidade de campo e os teores de argila, silte e areia. O ponto de inflexão calculado pode ser um estimador da capacidade de campo, o que pode facilitar e agilizar o cálculo de disponibilidade de água.

PALAVRAS-CHAVE: Manejo de irrigação, umidade do solo, curva de retenção de água do solo.

INTRODUCTION

Agricultural productivity is closely linked to soil physical attributes, specifically those that affect the soil-water relationship, as the soil is the primary source of water for plants (Rajkai et al. 2004). To properly manage irrigated crops, it is essential to understand the soil agronomic environment, particularly its physical and chemical properties (Melo et al. 2022). The interaction of water with soil characteristics is displayed in properties such as field capacity, which represents the moisture content of the soil after excessive water drainage. This parameter is crucial for the storage and availability of water for plants and is widely used in soil hydrology, management, irrigation and drainage engineering (Aguiar Netto et al. 1999, Dexter & Bird 2001, Keller et al. 2007, Dexter et al. 2008, Omuto & Gumbe 2009, Ottoni Filho et al. 2014, Schwen et al. 2014).

The concept of field capacity has been variously interpreted over the years, but its estimation is still considered very important in irrigation engineering calculations. Data on variation in the

[1] Received: Dec. 24, 2023. Accepted: Apr. 04, 2024. Published: Apr. 30, 2024. DOI: 10.1590/1983-40632024v5478125.
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percentage of soil water are necessary for soil preparation, calculations of irrigation projects and crop management (Mishra et al. 2015). Most of the water required for plant growth exists in the soil, what makes understanding the relationship among water, soil and plants crucial for an effective agricultural development (Ramos et al. 2023).

The correlation between soil hydraulic properties and its physical attributes has been extensively studied to better understand the relationship. For example, a previous investigation has examined the impact of clay, sand and organic matter content on soil water retention capacity (Wang et al. 2024). It is well known that the movement of soil moisture and its associated distributive processes are inherently complex. There are always uncertainties associated with any method, and the estimation of soil properties is likely to be the greatest source of variability in the process (Mishra et al. 2015, Herooty et al. 2020).

To increase the knowledge on the interactions between soil and water, Mueller et al. (2003) proposed the use of the inflection point of the characteristic curve of soil water retention, which corresponds to the field capacity. This technique generated significant results under conditions where the point was correlated with the moisture content, as determined at a tension of -6 kPa. In turn, Dexter et al. (2008) proposed that the inflection point of the water retention curve should be adjusted according to the van Genuchten (1980) model as the optimal point for soil preparation, in terms of moisture, and a field capacity equivalent to a tension of -10 kPa.

In the field, the determination of field capacity is expensive and requires much time, as many samples are required because of the large degree of spatial and temporal variability in the soil hydraulic properties. As an economic alternative, mathematical models using what are called pedotransfer functions were recognized as technically feasible and quickly adopted. The functions representing pedotransferences in soil are widely used in geosciences (Mello et al. 2005, Omuto & Gumbe 2009, Medeiros et al. 2014, Schwen et al. 2014, Montzka et al. 2017). Pedotransfer functions are equations that enable the estimation of difficult-to-determine hydraulic parameters using soil attribute values that are simpler to obtain (Mello et al. 2005, Montzka et al. 2017). Scattered information on soil water retention and availability can be grouped into databases to generate pedotransfer functions (Reichert et al. 2009). Minasny & Hartemink (2011) stated that pedotransfer functions are an important tool to compensate for the scarcity of soil data in many tropical countries. In this way, the volumetric water content in the determination of field capacity can be estimated as a function of the moisture level at the inflection point of the water retention curve and the total porosity for each soil horizon (Andrade & Stone 2011, Kumar et al. 2023).

Thus, this research aimed to determine the field capacity using equations derived from the retention curve and the inflection point for soils of various textures.

MATERIAL AND METHODS

The database used in this study consisted of 150 profiles extracted from publications by Embrapa (2022), encompassing data on textural classification, bulk density, particle density and soil water retention. Table 1 offers an overview of the soil properties included in this database, along with corresponding statistics such as the mean, standard deviation, minimum and maximum values for each textural class (Table 1).

Based on the database information, the soil water retention curves were adjusted for each profile using the model proposed by van Genuchten (1980): $\theta_h = \theta_r + \{(\theta_s - \theta_r)/[1 + [(\alpha \times h)^n]^m\}$, where θ_h is the soil water content (kg kg^{-1}); θ_r the soil residual water content (cm^3 cm^{-3}); θ_s the water content of the saturated soil (kg kg^{-1}); n a regression parameter of the equation; m the regression parameter of the equation representing the shape of the soil water retention curve; and $m = 1\text{-}1/n$. This parameter describes how fast the soil loses water as the soil water content decreases. The values of m typically range between 0 and 1, with lower values indicating a faster decrease in the water retention as the soil water content decreases, and higher values indicate a slower decrease. The parameter α has a dimension equal to the inverse of the tension (cm^{-1}), and h is the modulus of soil matrix potential (MPa).

Using the equation presented by Dexter & Bird (2001), the corresponding inflection point for each profile (θ_{Ip}) was generated: $\theta_{Ip} = (\theta_s - \theta_r)\ [1+ (1/m)]^{-m} + \theta_r$.

Multiple correlations were established among the volumetric water content in the field capacity (-33 kPa) and the clay (< 0.0002 mm), silt (0.0002-

Table 1. The database used contained 150 soil profiles with data on the textural composition of soils and moisture levels at field capacity and at the permanent wilting point.

Soil textural classification	Sand	Silt	Clay	Bulk density	Particle density	θ_{Fc}	θ_{PWP}
		$g\ kg^{-1}$			$g\ cm^{-3}$		$g\ g^{-1}$
Sandy (n = 50)							
Average	886.267	56.967	56.767	1.164	2.614	0.327	0.223
Standard deviation	47.803	36.333	34.124	0.118	0.101	0.115	0.088
Maximum	974.000	132.000	150.000	1.590	2.770	0.593	0.401
Minimum	790.000	5.000	17.000	1.010	2.370	0.129	0.095
Loamy (n = 50)							
Average	604.433	162.167	233.400	1.379	2.526	0.134	0.092
Standard deviation	132.506	65.175	126.216	0.253	0.211	0.038	0.036
Maximum	790.000	270.000	660.000	1.941	2.690	0.229	0.186
Minimum	180.000	50.000	110.000	1.030	1.720	0.076	0.051
Clayey (n = 50)							
Average	175.233	432.367	392.400	1.465	2.612	0.371	0.211
Standard deviation	150.582	134.555	199.113	0.137	0.116	0.145	0.102
Maximum	510.000	700.000	740.000	1.830	2.700	0.685	0.416
Minimum	10.000	250.000	20.000	1.230	2.060	0.143	0.058

θ_{Fc}: moisture at field capacity (-33 kPa); θ_{pwp}: moisture at permanent wilting point (-1,500 kPa); clay (< 0.0002 mm); silt (0.0002-0.05 mm); sand (0.05-0.02 mm); n: number of data pairs used to generate the equation. Source: Embrapa (2022).

0.05 mm) and sand (0.05-0.02 mm) contents of the samples. The quantitative expression of the moments of the hydraulic parameters, as functions of the soil particle size distribution, was derived using variance analysis and multiple linear regression techniques.

The performance of the regression calculations of the models was assessed graphically by the square root of the mean squared error (RMSE) and the standard error (SE): $RMSE = \sqrt{(1/N)} \sum(\theta_{meas} - \theta_{fitted})^2$ and $SE = (|\theta_{meas} - \theta_{fitted}|)/\theta_{meas}$, where N is the number of observations, θ_{fitted} the value estimated by the regression model of interest and θ_{meas} the value of the variable of interest measured.

RESULTS AND DISCUSSION

The particle size distribution in the data set is shown in Figure 1, where the lowest values for the inflection point were obtained for loamy soils. In sandy soils, the values of inflection points were closer to those of field capacity. As also shown in Figure 1, θ_{Fc} presents a determination coefficient (R^2) above 0.70 with θ_{Ip} in clayey soils, as well as the findings by Rahmati et al. (2018), who observed a positive correlation at the inflection point in clayey soils. Mueller et al. (2003) and Reichert et al. (2009) suggested that the plant-available water content varied with soil texture classes from 0.089 kg kg^{-1} for the sandy class to 0.191 kg kg^{-1} for the silty clay class. Conversely, the correlation of θ_{Fc} with θ_{Ip} in sandy and loamy soils was lower, being consistent with the findings of Carducci et al. (2011), what could be explained by the smaller specific surface of these soils, when compared with clayey soils.

Silva et al. (2015), in their study of θ_{Ip} with respect to θ_{Fc} and θ_{pwp}, observed that θ_{Ip} varied in the following order: sandy loam soil < loamy sand soil < loamy clay soil (with higher clay content). Lai & Ren (2016) asserted that there was no single effective average property for a heterogeneous field that could represent the water content profile of silty soil.

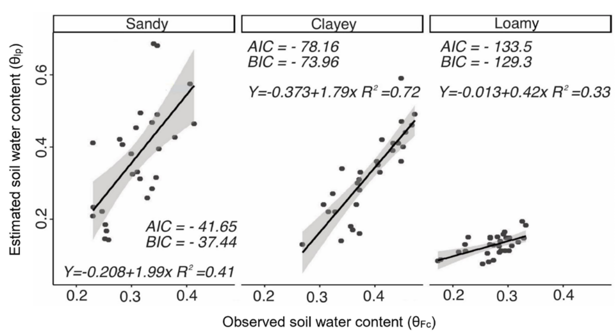

Figure 1. Correlation models between estimated water content by inflection point and water content measured at field capacity in sandy, loamy and clayey soils. R^2: coefficient of determination; AIC: Akaike information criterion; BIC: Bayesian information criterion. The gray hatched area represents a confidence interval of 95 %.

The soils with clayey textures were those that presented the highest coefficients for determining the soil water content at field capacity (θ_{Fc}), confirming the strong influence of clay on soil water retention, being the only textural component used to adjust pedotransfer functions (Giarola et al. 2002, Silva et al. 2015). Thus, Carducci et al. (2011) stated that the clay content in soils play a crucial role in water retention by increasing the capillarity and the adsorption of water, what is consistent with the idea that total clay content is the main attribute directly related to water retention in highly weathered soils. In essence, the weathering process in soils leads to an augmented proportion of fine particles, progressively enhancing water adsorption owing to the high energy retained within the intra-microaggregate pores. This is mainly due to the greater number of micropores and menisci existing in a textured clay soil, in comparison with a sandy soil, increasing the capillary forces and providing a fine-textured soil with greater ability to retain water under more negative matrix potentials. The larger the particle size in a sandy soil, the lower the water retention will be (Casaroli & van Lier 2008, Reichert et al. 2009, Silva et al. 2015).

Another factor to consider is the type of clay present in the soil, as the mineral type of the clay fraction dictates the amount of water that a soil can retain (Medeiros et al. 2014). Reis et al. (2018), using the Splintex 1.0 model to approximate soil water retention curves, demonstrated that when the clay content exceeds 50 %, the correlation with soil water retention curves begins to decrease. Mueller et al. (2003) suggested that the variations in inflection point estimates could be attributed to differences in the soil retention curve, being notable in soils with a very steep retention curve and rendering the inflection point estimate less reliable.

When compared with the physico-hydric attributes that produced the highest values of R^2 (Figure 2), the strongest correlation of θ_{Ip} seems to be with bulk density and total soil porosity, followed by the sand and clay contents. This aligns with the findings of Andrade & Stone (2011), who stated that the inflection point is strongly correlated with bulk density and total porosity. Qiao et al. (2018) considered bulk density as one of the most crucial variables due to its significant contributions to variations in all soil hydraulic properties, what may explain 87.0, 89.7, 94.8 and 91.2 % of the total variance in saturated hydraulic conductivity (K_s), saturated water content (θ_s), α and n empirical shape parameters, respectively, in the van Genuchten model. However, the soil physical properties, such as bulk density and textural class, accounted for variations in its hydraulic properties. Thus, Mello et al. (2005) reported that the variables demonstrating greater significance were associated with textural attributes, influencing the soil-water

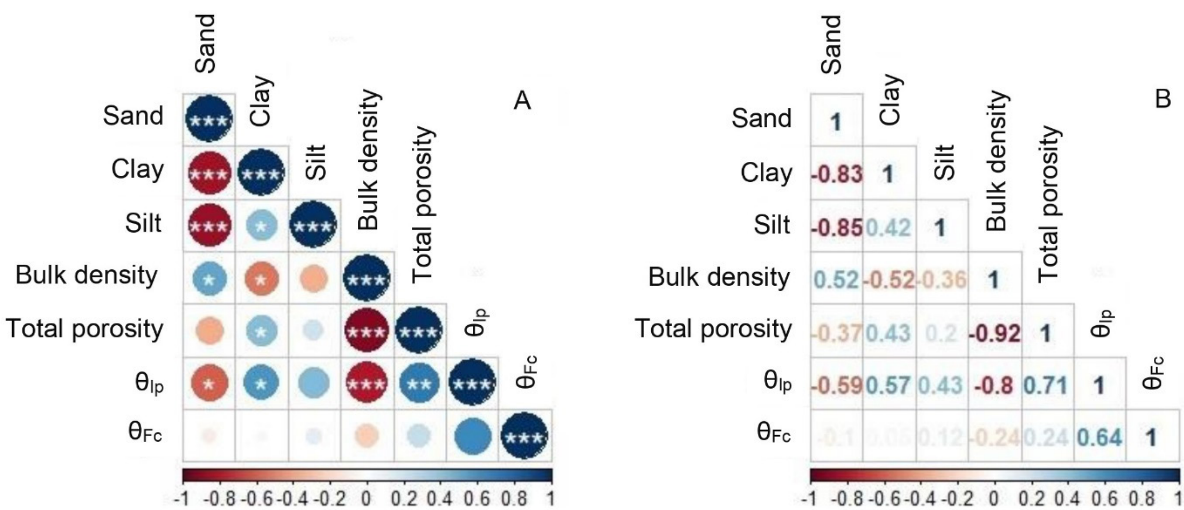

Figure 2. Correlation map (correlogram) of sand, clay and silt contents, soil bulk density, total porosity, moisture level at field capacity by the inflection point (θ_{Ip}) and moisture level by the standard method (θ_{Fc}) (determined at a tension table or Richard's plate). Blue circles correspond to significant positive correlations and red circles to significant negative correlations. A) the circle size reflects the magnitude of the Pearson's correlation coefficient; B) significant Pearson's correlation coefficients of $p \leq 0.001$***, $p < 0.01$** and $p < 0.05$*.

retention curve. This coincides with the findings of Ottoni Filho et al. (2014), who stated that the most effective pedotransfer functions include only textural information, specifically clay and sand contents.

Taking into account the soil database variables related to the particle size distribution, with direct and indirect relationships to θ_{Ip} and θ_{Fc}, it was possible to estimate the water content in θ_{Fc} using the pedotransfer functions outlined in Table 2. The coefficients of determination for the proposed pedotransfer functions ranged from 0.41 in sandy soils to 0.85 in clayey soils. Hence, in sandy textures, the equation incorporating not only particle distributions, but also total soil porosity and particle density, exhibited the highest correlation coefficient, with R^2 of 0.78, denoted as the equation: θ_{Fc} = -0.0000751sand + 0.0002212clay - 0.1300tp - 0.3293sd + 0.9016, which, for medium-textured soils, becomes: θ_{Fc} = 1.1832292θ_{Ip} - 0.3818tp - 0.01660, and, for clayey soils, is given as: θ_{Fc} = -0.0003065sand + 0.0002124silt - 0.358tp - 0.4384sd + 1.0068.

With two independent variables, this equation also yielded a strong correlation of R^2 = 0.777 and demonstrated the highest correlation coefficient of 0.851. However, the use of θ_{Ip} to determine θ_{Fc} proved to be more effective in loamy soils, with clayey and sandy soils showing less favorable performances in this relationship.

The results in table 2 corroborate those found by Mello et al. (2005) and Ottoni Filho et al. (2014), who highlighted the importance of the soil physical attributes in the estimation of θ_{Fc} and found that the most significant correlations after the relationship with soil moisture retention data were for those that considered the sandy and clay content, resulting in values of R^2 between -0.65 and -0.72 for sandy soils and 0.481 and 0.628 for clayey soils, depending on the size of the database.

Arya & Paris (1981) found that the most effective model for estimating soil water moisture was the one that established a relationship between particle size and bulk density to determine the characteristics of soil moisture. Medeiros et al. (2014), employing pedotransfer functions based on the particle size distributions from other authors, obtained R^2 values of 0.70, 0.15, 0.09, 0.13 and 0.11 for θ_{Fc}, along with corresponding RMSE values of 0.05, 0.14, 0.19, 0.07 and 0.09 m m^{-3}. Reichert et al. (2009), using only granulometric distribution data, found determination coefficients of pedotransfer functions for estimated gravimetric soil water content between 0.44 and 0.54. Overall, the standard error values ranged from 0.021 to 0.063 m^3 m^{-3}, and these were considered low values. As indicated by Tomasella et al. (2000), higher values of standard error typically result from dispersion in measurements, signifying inconsistent data, parameters that are poorly defined and inadequate fits, especially in curves with fewer measured data points.

Table 2. Moisture estimates at field capacity (F_c) determined by equations taking into account the proportions of sand, silt and clay, soil bulk density (sd), total porosity (tp) and inflection point (I_p), and their respective coefficient of determination (R^2), root mean-square error (RMSE) and standard error (SE), among 150 soil profiles.

Equations	SE	RMSE	R^2
Sandy			
θ_{Fc} = -0.0000751sand + 0.0002212clay - 0.1300tp - 0.3293sd + 0.9016	0.025	2.276	0.780
θ_{Fc} = -0.002801sand - 0.002543silt + 0.726860tp + 2.680564	0.101	9.413	0.564
θ_{Fc} = -0.0001866sand + 0.002340clay - 0.32981sd + 0.8866	0.102	9.501	0.556
θ_{Fc} = 1.88860θ_{Ip} - 0.21117	0.113	10.925	0.413
θ_{Fc} = 2.46350780θ_{Ip} + 0.2427042sd - 0.743845	0.114	10.789	0.427
Loamy			
θ_{Fc} = 1.1832920θ_{Ip} - 0.3818tp - 0.01660	0.021	1.957	0.777
θ_{Fc} = -0.0000564clay - 0.0003021sand - 0.0964sd + 0.45778	0.021	1.990	0.716
θ_{Fc} = -0.0001909clay + 0.0000234silt - 0.17019sd - 0.20986tp + 0.57209	0.020	1.871	0.750
Clayey			
θ_{Fc} = -0.0003065sand + 0.0002124silt - 0.358tp - 0.4384sd + 1.0068	0.048	4.344	0.851
θ_{Fc} = -0.000518sand - 0.000195clay - 0.3271sd + 0.8833	0.047	4.377	0.849
θ_{Fc} = 1.791110θ_{Ip} - 0.373386	0.062	5.957	0.720
θ_{Fc} = 1.86650θ_{Ip} + 0.042710sd - 0.452606	0.063	5.950	0.721

θ_{Fc}: moisture at field capacity; θ_{Ip}: moisture at the inflection point.

CONCLUSIONS

1. Equations derived from the water retention curve and soil physical attributes can be used to determine the field capacity in different soil textures. In clayey soils, the determination coefficient (R^2) obtained from the relationship between observed and estimated soil water content values was 0.72. The root mean-square error (RMSE) and standard error (SE) values were lower in general, showing the potential of the generated equations for accurately estimating the field capacity of different soils types;
2. The calculated soil water retention curve's inflection point is a reliable indicator of field capacity for soils with high clay content, making it easier and quicker to calculate water availability. It serves as a valuable tool for irrigation management to conserve water and ensure the sustainability of agricultural production systems.

ACKNOWLEDGMENTS

This study was partially financed by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (Capes; Finance Code 001).

REFERENCES

AGUIAR NETTO, A. O.; NACIF, P. G. S.; REZENDE, J. O. Avaliação do conceito de capacidade de campo para um Latossolo Amarelo coeso do estado da Bahia. *Revista Brasileira de Ciência do Solo*, v. 23, n. 3, p. 661-667, 1999.

ANDRADE, R. da S.; STONE, L. F. Estimativa da umidade na capacidade de campo em solos sob Cerrado. *Revista Brasileira de Engenharia Agrícola e Ambiental*, v. 15, n. 2, p. 111-116, 2011.

ARYA, L. M.; PARIS, J. F. A physicoempirical model to predict the soil moisture characteristic from particle-size distribution and bulk density data. *Soil Science Society of America Journal*, v. 45, n. 6, p. 1023-1030, 1981.

CARDUCCI, C. E.; OLIVEIRA, G. C. de; SEVERIANO, E. da C.; ZEVIANI, W. M. Modelagem da curva de retenção de água de Latossolos utilizando a Equação Duplo Van Genuchten. *Revista Brasileira de Ciência do Solo*, v. 35, n. 1, p. 77-86, 2011.

CASAROLI, D.; VAN LIER, Q. de J. Critérios para determinação da capacidade de vaso. *Revista Brasileira de Ciência do Solo*, v. 32, n. 1, p. 59-66, 2008.

DEXTER, A. R.; BIRD, N. R. A. Methods for predicting the optimum and the range of soil water contents for tillage based on the water retention curve. *Soil & Tillage Research*, v. 57, n. 4, p. 203-212, 2001.

DEXTER, A. R.; CZYZ, E. A.; RICHARD, G.; RESZKOWSKA, A. A user-friendly water retention function that takes account of the textural and structural pore spaces in soil. *Geoderma*, v. 143, n. 3-4, p. 243-253, 2008.

EMPRESA BRASILEIRA DE PESQUISA AGROPECUÁRIA (Embrapa). *Soil database*. 2022. Available at: https://www.bdsolos.cnptia.embrapa.br/consulta_publica.html. Access on: June 8, 2023.

GIAROLA, N. F. B.; SILVA, A. P.; IMHOFF, S. Relações entre propriedades físicas e características de solos da região Sul do Brasil. *Revista Brasileira de Ciência do Solo*, v. 26, n. 4, p. 885-893, 2002.

HEROOTY, Y.; BAR (KUTIEL), P.; YIZHAQ, H.; KATZ, O. Soil hydraulic properties and water source-sink relations affect plant rings' formation and sizes under arid conditions. *Flora*, v. 270, e151664, 2020.

KELLER, T.; ARVIDSSON, J.; DEXTER, A. R. Soil structures produced by tillage as affected by soil water content and the physical quality of soil. *Soil and Tillage Research*, v. 92, n. 1-2, p. 45-52, 2007.

KUMAR, H.; SRIVASTAVA, P.; LAMBA, J.; LENA, B.; DIAMANTOPOULOS, E.; ORTIZ, B.; TAKHELLAMBAM, B.; MORATA, G.; BONDESAN, L. A methodology to optimize site-specific field capacity and irrigation thresholds. *Agricultural Water Management*, v. 286, e108385, 2023.

LAI, J.; REN, L. Estimation of effective hydraulic parameters in heterogeneous soils at field scale. *Geoderma*, v. 264, n. 1, p. 28-41, 2016.

MEDEIROS, J. C.; COOPER, M.; DALLA ROSA, J.; GRIMALDI, M.; COQUET, Y. Assessment of pedotransfer functions for estimating soil water retention curves for the Amazon region. *Revista Brasileira de Ciência do Solo*, v. 38, n. 3, p. 730-743, 2014.

MELLO, C. R.; OLIVEIRA, G. C.; FERREIRA, D. F.; LIMA, J. M.; LOPES, D. Modelos para determinação dos parâmetros da equação de van Genuchten para um Cambissolo. *Engenharia Agrícola*, v. 9, n. 1, p. 23-29, 2005.

MELO, L. L. de; MELO, V. G. M. L. de; MARQUES, P. A. A.; FRIZZONE, J. A.; COELHO, R. D.; ROMERO, R. A. F.; BARROS, T. H. da S. Deep learning for identification of water deficits in sugarcane based on thermal images. *Agricultural Water Management*, v. 272, e107820, 2022.

MINASNY, B.; HARTEMINK, A. E. Predicting soil properties in the tropics. *Earth-Science Reviews*, v. 106, n. 1-2, p. 52-62, 2011.

MISHRA, V.; ELLENBURG, W. L.; AL-HAMDAN, O. Z.; BRUCE, J.; CRUISE, J. F. Modeling soil moisture profiles in irrigated fields by the principle of maximum entropy. *Entropy*, v. 17, n. 6, p. 4454-4484, 2015.

MONTZKA, C.; HERBST, M.; WEIHERMÜLLER, L.; VERHOEF, A.; VEREECKEN, H. A global data set of soil hydraulic properties and sub-grid variability of soil water retention and hydraulic conductivity curves. *Earth System Science Data*, v. 9, n. 2, p. 529-543, 2017.

MUELLER, L.; SCHINDLER, U.; FAUSEY, N. R.; LAL, R. Comparison of methods for estimating maximum soil water content for optimum workability. *Soil and Tillage Research*, v. 72, n. 1, p. 9-20, 2003.

OMUTO, C. T.; GUMBE, L. O. Estimating water infiltration and retention characteristics using a computer program in R. *Computers & Geosciences*, v. 35, n. 3, p. 579-585, 2009.

OTTONI FILHO, T. B.; OTTONI, M. V.; OLIVEIRA, M. B. de; MACEDO, J. R. de; REICHARDT, K. Revisiting field capacity (FC): variation of definition of FC and its estimation from pedotransfer functions. *Revista Brasileira de Ciência do Solo*, v. 38, n. 6, p. 1750-1764, 2014.

QIAO, J.; ZHU, Y.; JIA, X.; HUANG, L.; SHAO, M. Estimating the spatial relationships between soil hydraulic properties and soil physical properties in the critical zone (0-100 m) on the Loess Plateau, China: a state-space modeling approach. *Catena*, v. 160, n. 1, p. 385-393, 2018.

RAHMATI, M. et al. Development and analysis of the soil water infiltration global database. *Earth System Science Data*, v. 10, n. 3, p. 1237-1263, 2018.

RAJKAI, K.; KABOS, S.; VAN GENUCHTEN, M. T. Estimating the water retention curve from soil properties: comparison of linear, nonlinear and concomitant variable methods. *Soil and Tillage Research*, v. 79, n. 2, p. 145-152, 2004.

RAMOS, T. B.; DAROUICH, H.; GONÇALVES, M. C. Development and functional evaluation of pedotransfer functions for estimating soil hydraulic properties in Portuguese soils: implications for soil water dynamics. *Geoderma Regional*, v. 35, e00717, 2023.

REICHERT, J. M.; ALBUQUERQUE, J. A.; KAISER, D. R.; REINERT, D. J.; URACH, F. L.; CARLESSO, R. Estimation of water retention and availability in soils of Rio Grande do Sul. *Revista Brasileira de Ciência do Solo*, v. 33, n. 6, p. 1547-1560, 2009.

REIS, A. M. H. dos; ARMINDO, R. A.; DURÃES, M. F.; VAN LIER, Q. de J. Evaluating pedotransfer functions of the Splintex model. *European Journal of Soil Science*, v. 69, n. 4, p. 685-697, 2018.

SCHWEN, A.; ZIMMERMANN, M.; BODNER, G. Vertical variations of soil hydraulic properties within two soil profiles and its relevance for soil water simulations. *Journal of Hydrology*, v. 516, n. 1, p. 169-181, 2014.

SILVA, T. T. S.; MONTEIRO, D. R.; ALMEIDA, B. G.; FIRMINO, M. C.; LIMA, V. L. A. Comportamento da curva de retenção de água em diferentes tipos de solo. *In*: CONGRESSO TÉCNICO CIENTÍFICO DA ENGENHARIA E DA AGRONOMIA, 2015, Fortaleza. *Anais...* Fortaleza: Confea, 2015. p. 18-21

TOMASELLA, J.; HODNETT, M. G.; ROSSATO, L. Pedotransfer functions for the estimation of soil water retention in Brazilian soils. *Soil Science Society of America Journal*, v. 64, n. 1, p. 327-338, 2000.

VAN GENUCHTEN, M. T. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. *Soil Science Society of America Journal*, v. 44, n. 5, p. 892-898, 1980.

WANG, Z.; HUANG, L.; SHAO, M. Development of pedotransfer functions for predicting hydraulic parameters of van Genuchten model by incorporating environmental variables on the Qinghai-Tibet Plateau. *Soil and Tillage Research*, v. 236, e105952, 2024.