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Improved understanding of soil water content at field capacity and estimates from pedotransfer functions

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Abstract

The soil water content at field capacity, θ_{FC}, is a fundamental variable for irrigation and agriculture. This study determines the optimal tension (−33 or −10 kPa) of deriving θ_{FC} which best matches the *in situ* field measurements following the Veihmeyer procedure. The Veihmeyer method refers to a profile water status for which there is a negligible drainage rate of bare soil without evaporation. In addition, we derive a set of linear and nonlinear pedotransfer functions (PTFs) which estimate θ_{FC}. θ_{FC} was measured in 69 plots in north-western Iran, which has a cold semi-arid climate. The soil properties used for developing PTFs include texture, bulk density, and organic matter. The results show that θ_{FC} cannot be derived at a fixed tension. We therefore developed PTFs with satisfactory performance in reproducing *in situ* measured θ_{FC}. The findings show that PTFs developed at a fixed tension consistently underestimate θ_{FC} derived *in situ*. It was also speculated that tension less than −10 kPa could yield improved predictions of *in situ* θ_{FC}.

KEYWORDS

aeration capacity, pedotransfer functions, soil physical properties, soil water content, soil water retention, Veihmeyer drainage

Résumé

La teneur en eau du sol à la capacité du terrain, θ_{FC}, est une variable fondamentale pour l'irrigation et l'agriculture. Cette étude détermine la tension optimale (−33 kPa ou −10 kPa) de dérivation de θ_{FC}, qui correspond le mieux aux mesures de terrain in situ suivant la procédure de Veihmeyer. La méthode de Veihmeyer se réfère à un état de l'eau de profil pour lequel il existe un taux de drainage négligeable du sol nu sans évaporation. En outre, nous dérivons un ensemble de fonctions de pédotransfert linéaires et non linéaires (PTF) qui

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estiment θ_{FC}. θ_{FC} a été mesuré sur 69 parcelles au nord-ouest de l'Iran, où il existe un climat froid semi-aride. Les propriétés du sol utilisées pour l'élaboration des PTF comprennent la texture, la densité apparente et la matière organique. Les résultats montrent que θ_{FC} ne peut pas être dérivé à une tension fixe. Nous avons donc développé des PTF avec des performances satisfaisantes dans la reproduction de θ_{FC} mesuré in situ. Les résultats montrent que les PTF développés à une tension fixe sous-estiment systématiquement θ_{FC} dérivé in situ. On a également émis l'hypothèse que la tension inférieure à −10 kPa pourrait permettre de mieux prédire la présence in situ de θ_{FC}.

MOTS CLÉS

teneur en eau du sol, rétention d'eau du sol, capacité d'aération, propriétés physiques du sol, fonctions de pédotransfert, drainage de Veihmeyer

1 | INTRODUCTION

The soil water content at field capacity, θ_{FC}, is a semi-physical quantity which is commonly used for irrigation management. Most irrigation practices require information on θ_{FC}, which can be obtained either in the field or in the laboratory (Yi et al., 2013). The concept of θ_{FC} was introduced by Veihmeyer and Hendrickson (1931) and refers to a profile water status that corresponds to a negligible drainage rate. Meyer and Gee (1999) recommended values for unsaturated hydraulic conductivity to estimate θ_{FC} based on soil texture: 0.1, 0.01, and 0.001 cm day^{-1} for sandy, loamy, and clay soils, respectively. Gravity water withdrawal can vary from approximately 24 h in coarse-textured soils to more than 48 h in fine-textured soils and 2–3 weeks for volcanic soils (Will & Stone, 1968). The time to reach equilibrium also depends on the soil organic matter (SOM), soil structure, and other factors (Aschonitis et al., 2013; Kirkham, 2005; Rasoulzadeh & Raoof, 2014). θ_{FC} has applications in irrigation scheduling but can also be interpreted as an upper limit of available water content in bucket models for soil water balance. Nevertheless, physically based models that solve Richards' equation do not use θ_{FC} (Pollacco et al., 2022).

Various authors have found that θ_{FC} varies between tension of −50 and −5 kPa (e.g. Colman, 1947; Evett et al., 2019; Lyon & Buckman, 1943; Nemes et al., 2011; Romano & Santini, 2002; Turek et al., 2019). It is commonly accepted in the literature that θ_{FC} is estimated either at a tension of −33 kPa or at −10 kPa (e.g. Hillel, 1998; Kirkham, 2005; Libohova et al., 2018; Meyer & Gee, 1999; Robertson et al., 2021). However, it is important to note that θ_{FC} cannot be derived at a fixed tension. The tension at which θ_{FC} is defined is influenced by texture; water held at −33 kPa is mainly used to determine the θ_{FC} for clayey and loamy soils, whereas −10 kPa is mainly used for sandy soils (Libohova et al., 2018; Robertson et al., 2021). Although there are inherent inconsistencies in this definition, the soil water content at −33 kPa is widely accepted (Kirkham, 2005).

Hillel (1998) argued that measuring θ_{FC} in the field is necessary to account for the hydrodynamic nature of water in soil. The conventional method of approximating θ_{FC} based on the tension at −10 kPa or −33 kPa does not align with the definition of θ_{FC}, as it fails to fully drain the soil (e.g. Hillel, 1998; Meyer & Gee, 1999). Thus, there is no standard tension which estimates θ_{FC} in the laboratory that corresponds to negligible drainage flux, making the definition of θ_{FC} with a fixed tension inaccurate.

The tension at which θ_{FC} is computed also depends on SOM which increases the saturated soil soil water content, and improves the soil structure and aggregation, thus affecting the tension at which θ_{FC} is computed. Rawls et al. (2003) showed that an increase in SOM increases the water-holding capacity in sandy soils (decreases tension which describes θ_{FC}) but decreases the water-holding capacity of fine-textured soils (increases tension which describes θ_{FC}).

It is best practice to irrigate the soil until it reaches θ_{FC}, because irrigating above θ_{FC} would cause it to quickly lose water through internal drainage. An improved estimation of θ_{FC} would improve the accuracy of modelling crop growth (de Jong van Lier, 2017), and save irrigation water (Rai et al., 2017).

The *in situ* measurement of θ_{FC} is time-consuming and costly but is believed to provide a more accurate definition of θ_{FC}. These values are also used to develop pedotransfer functions (PTFs), which we are proposing.

The objective of this research is to determine at what tension (−10 or −33 kPa) θ_{FC} should be derived by comparing laboratory measurements with *in situ* θ_{FC} measurements across a variety of Iranian soils with contrasting textures. The performance of some classic PTFs is evaluated, and a new set of PTFs is presented. This paper is organized as follows: Section 2 describes the data and methodology used; Section 3 compares *in situ* measurements of θ_{FC} with laboratory estimates, evaluates the performance of a set of selected PTFs from the literature to estimate θ_{FC}, and derives and evaluates a new set of PTFs based on *in situ* θ_{FC} measurements; finally, the main conclusions are summarized in Section 4.

2 | MATERIALS AND METHODS

2.1 | Site description

This study was carried out in Khalkhal County, which is situated in the Ardabil Province of north-western Iran, spanning from 48° 27′ to 48° 36′ E longitude to 37° 30′ to 37° 42′ N latitude (Figure 1). Based on the Köppen climate classification, Ardabil Province experiences a cold semi-arid steppe climate, with a long-term average annual rainfall of 409.3 mm and an air temperature of 9.6°C, which fluctuates from 3.2 to 16.0°C (Meteorological Organization of Iran, 2023).

The United States Department of Agriculture (USDA) texture classification of the soils in the study area includes *loam, sandy loam, clay loam, loamy sand, sandy clay loam, and silty loam*, as described in the triangle texture (Figure 3).

2.2 | Experimental set-up, field measurements, and sampling

An accurate technique for deriving θ_{FC} in the field involves saturating a bare soil profile and then covering it with a vinyl sheet to prevent evaporation. Furthermore, vegetation was removed from the soil surface to prevent transpiration. The water content was subsequently monitored over time until drainage became negligible (Turek et al., 2020).

To determine the θ_{FC} in the field, we selected 69 plots. At each measuring point, we dug a depression with a surface area of 2×2 m^2 and a depth of 0.3 m (Figure 1). We poured 2 m^3 of water into each plot, which assumed that approximately 1 m of the soil profile became saturated (Figure 2a). After ponding ceased, the surface of each plot was covered with two layers of dark plastic to prevent evaporation (Figure 2b). The water content was measured by taking cores of 100 cm^3 at the soil surface. Every core was taken approximately from the middle of each plot. The plots were deliberately larger than the sample size to minimize lateral water movement in the sampling area. To prevent water loss from the samples before weighing, they were promptly placed in plastic bags, packed, and transported under chilled conditions to the laboratory.

The water content was measured daily until the differences in water content over two consecutive days were negligible (<1%). At this point, it was assumed that all the gravitational water had drained and that the soil water content was entrapped in the small pores; therefore, it was assumed that θ_{FC} was reached. In particular, for fine-textured soil, it can take over 5 days to reach θ_{FC}.

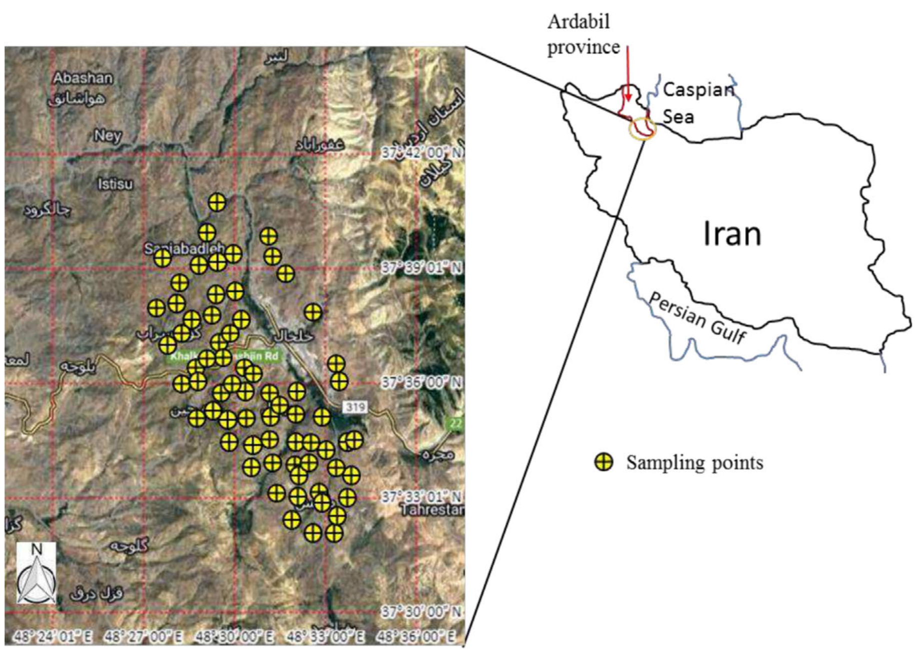

FIGURE 1 Sampling points in the study area.

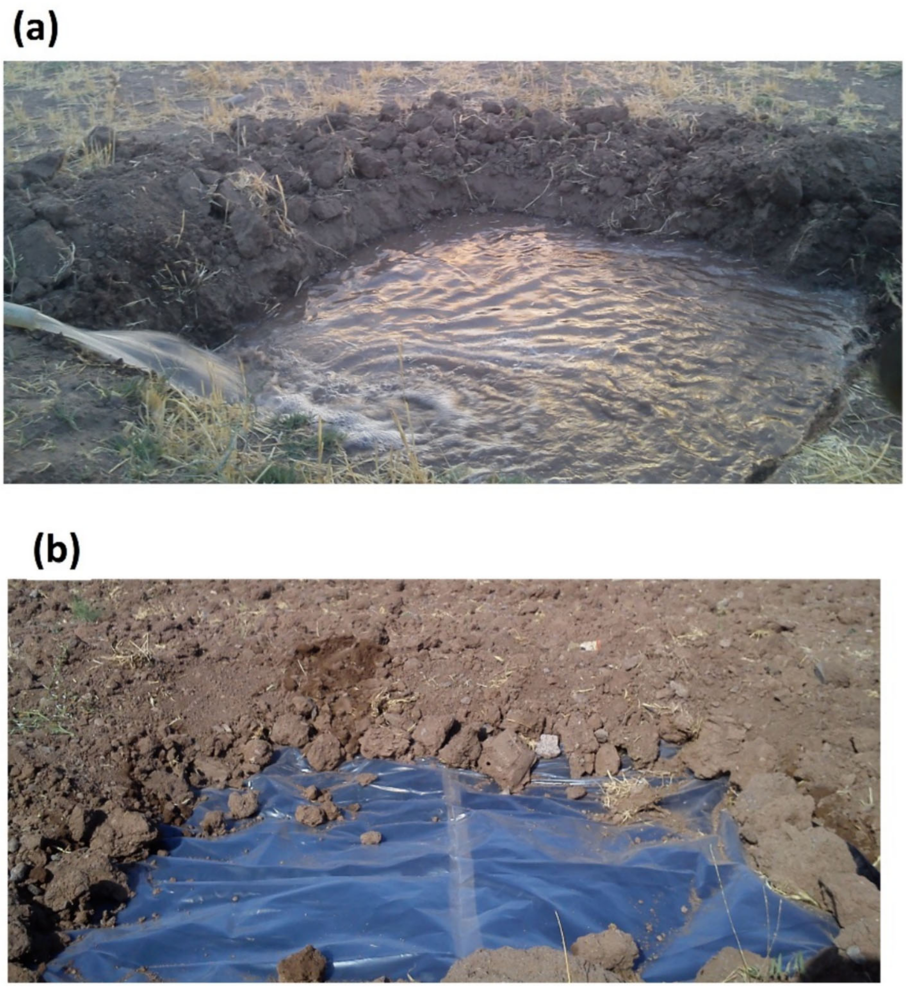

FIGURE 2 (a) Water was applied to the plot, and (b) the plot was covered with two layers of dark plastic to prevent evaporation.

Therefore, measurements for the 69 plots by using this technique were found to be time-consuming.

Disturbed and undisturbed samples were extracted from the plots to measure dry bulk density (BD), SOM, and water content at −33 and −10 kPa (θ_{33} and θ_{10}), along with measuring soil texture. To ensure accuracy, laboratory analysis was repeated in at least three replicates for each designated soil property and plot location.

2.3 | Laboratory measurements

The water content was measured in the laboratory using the standard oven-dry method. The BD was measured on undisturbed cores taken with 100 cm^3 stainless steel cylinders (5 cm internal diameter and 5.1 cm height). The samples were oven-dried at 105°C for 24 h, and the BD was calculated by dividing the oven dry mass of the soil by the volume of the soil via the procedure described by Grossman and Reinsch (2002). The measurements of other soil properties (texture, SOM) were performed on disturbed soil samples, which were air-dried and sieved at 2 mm to remove the coarse fragments. The particle size distribution (sand, silt, and clay) was determined via the sieving method following Gee and Or (2002). The soil particle density (PD) was measured via a glass pycnometer; 10 g of air-dried (< 2 mm) soil sample was placed in the pycnometer, and the displaced volume of distilled water was determined. The total porosity (φ) can be obtained from the BD and PD in units of g cm^{-3} via the following equation: $\varphi = 1 - BD/PD$. The soil organic carbon (SOC) was determined via the wet oxidation method, which uses potassium dichromate derived from an acidic environment followed by titration with ferrous ammonium sulfate (e.g. Mingorance et al., 2007; Walkley & Black, 1934). SOC was converted to SOM by using the van Bemmelen factor (1.724), which assumes that SOC is approximately 58% of SOM (Huntington, 2007).

Undisturbed soil cores (100 cm^3) were used to measure θ_{33} and θ_{10} which were previously saturated over a period of 24 h, by using a ceramic pressure plate extractor at −10 and −33 kPa (e.g. Rasoulzadeh et al., 2022; Reynolds & Elrick, 2002).

2.4 | PTFs to estimate θ_{FC}

The PTFs for estimating θ_{FC} are traditionally derived from laboratory measurements at −10 or −33 kPa. Nevertheless, this is ambiguous because, as highlighted in the introduction, the tension at which θ_{FC} should be computed such that drainage is negligible depends on the soil make-up (e.g. Inforsato & de Jong Van Lier, 2021; Nasta & Romano, 2016; Romano et al., 2011). The novelty of this study is that θ_{FC} is derived with *in situ* measurements of θ_{FC}, as described in Section 2.2. Thus, PTFs were derived by using predictor variables of texture (sand, silt, and clay), BD, and SOC. SPSS V.16 software was used for the development and statistical analysis of the PTFs.

2.4.1 | Linear PTFs

For linear PTFs, θ_{FC} is a function of the combination of soil predictors as follows:

$$\theta_{FC} = b + a_1x_1 + a_2x_2 + a_3x_3 + \dots \quad (1)$$

where b, a_1, a_2, and a_3 are fitting parameters and x_1, x_2, and x_3 are predictive soil properties.

Previous studies have shown the capabilities of linear PTFs to predict θ_{FC}, which requires only textural information. For example, Botula (2013), Minasny and Hartemink (2011), and Adhikary et al. (2008) developed PTFs to estimate θ_{FC} using sand as the sole input parameter, whereas Tomasella and Hodnett (1998) used silt and clay. Further improvements have been made to the accuracy of PTFs by including BD as a predictor (e.g. Salchow et al., 1996; Balland et al., 2008; Minasny & Hartemink, 2011; Touil et al., 2016). It has also been shown that using SOC as a predictor can increase the accuracy of PTFs (e.g. Balland et al., 2008; Minasny & Hartemink, 2011). Nevertheless, these PTFs were developed based on laboratory measurements at −33 kPa and not by using *in situ* data.

2.4.2 | Nonlinear PTFs

Nevertheless, one of the greatest drawbacks of linear PTFs encountered in the literature is that they have restrictions on the range of the predictors, not all of which yield acceptable results for all SOM and textural combinations (from 0 to 100%) (e.g. Rawls et al., 2003; Rawls & Brakensiek, 1985). Many PTFs have restrictions on the range of BD. Therefore, there is a need to develop nonlinear PTFs that yield accurate results over a wide range of soil conditions (e.g. Pollacco, 2008). Additionally, Pollacco (2008) reported that nonlinear PTFs are superior to linear PTFs because they predict a nonlinear physical relationship between clay and θ_{FC} (Hillel, 1998). For example, Pollacco (2008) proposed two reliable nonlinear PTFs to estimate θ_{FC}, which produces satisfactory results using exponential functions. The list of nonlinear PTFs for estimating θ_{FC} tested in this work are shown in Table 1.

2.5 | Evaluation criteria

The values of θ_{FC} measured via the models described in Table 1 were compared via five statistical indexes: the root mean square error (RMSE), the geometric mean error ratio (GMER), the normalized root mean square error (NRMSE), the mean error (ME), and the modified index of agreement (d') (e.g. Legates & McCabe, 1999; Li et al., 2013; Zakizadeh Abkenar & Rasoulzadeh, 2019). These are summarized as follows:

TABLE 1 List of selected non-linear PTFs for estimating θ_{FC}.

	θ_{FC} (cm^3 cm^{-3})
Nonlinear PTF-1	$\varphi \times [p_{min} + (p_{max} - p_{min}) \times \text{clay}^{p_{clay}}]$ with $p_{min} \le \frac{\theta_{FC}}{\varphi} \le p_{max}$, $0 < p_{min} < p_{max} \le 1$ and $p_{clay} > 0$
Nonlinear PTF-2	$\varphi \times [p_{min} + (p_{max} - p_{min}) \times \text{clay}^{p_{clay}}] \times \text{EXP}\left(\frac{p_{sand} \times \text{sand}^{d}}{\varphi}\right)$ with $p_{sand} \ge 0$
Nonlinear PTF-3	$a_1\varphi + a_2\text{clay}^{b_1}$
Nonlinear PTF-4	$a_3\varphi + a_4\text{clay}^{b_2} + a_5\text{sand}^{b_3}$
Non-linear PTF-5	$a_6\varphi + a_7\text{clay}^{b_4} + a_8\text{sand}^{b_5} + a_9\,\text{SOC}^{b_6}$

φ: porosity (m^3 m^{-3}); SOC: soil organic carbon (%); Clay, Silt, and Sand are percentages; p_{min}, p_{max}, p_{clay}, p_{sand}, a_1, a_2, ..., a_9, b_1, b_2, ..., b_6, and d are fitting parameters.

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(M_i - P_i)^2} \tag{2}$$

$$\mathrm{GMER} = \mathrm{Exp}\left(\frac{1}{n}\sum_{i=1}^{n}\ln\left(\frac{P_i}{M_i}\right)\right) \tag{3}$$

$$\mathrm{NRMSE} = \frac{\mathrm{RMSE}}{\overline{M}} \times 100 \tag{4}$$

$$\mathrm{ME} = \frac{1}{n}\sum_{i=1}^{n}(M_i - P_i) \tag{5}$$

$$d' = 1 - \frac{\sum_{i=1}^{n}|M_i - P_i|}{\sum_{i=1}^{n}\left(\left|P_i - \overline{M}\right| + \left|M_i - \overline{M}\right|\right)} \tag{6}$$

TABLE 2 Mean, minimum (min), maximum (max), and standard deviation (SD) values of the selected soil properties of the 69 samples.

	Mean	Min	Max	SD
Sand (%)	46	22	84	16
Silt (%)	34	9	56	9
Clay (%)	20	2	44	10
Bulk density (g cm^{-3})	1.43	1.08	1.71	0.13
Soil organic carbon (%)	1.16	0.20	3.28	0.66

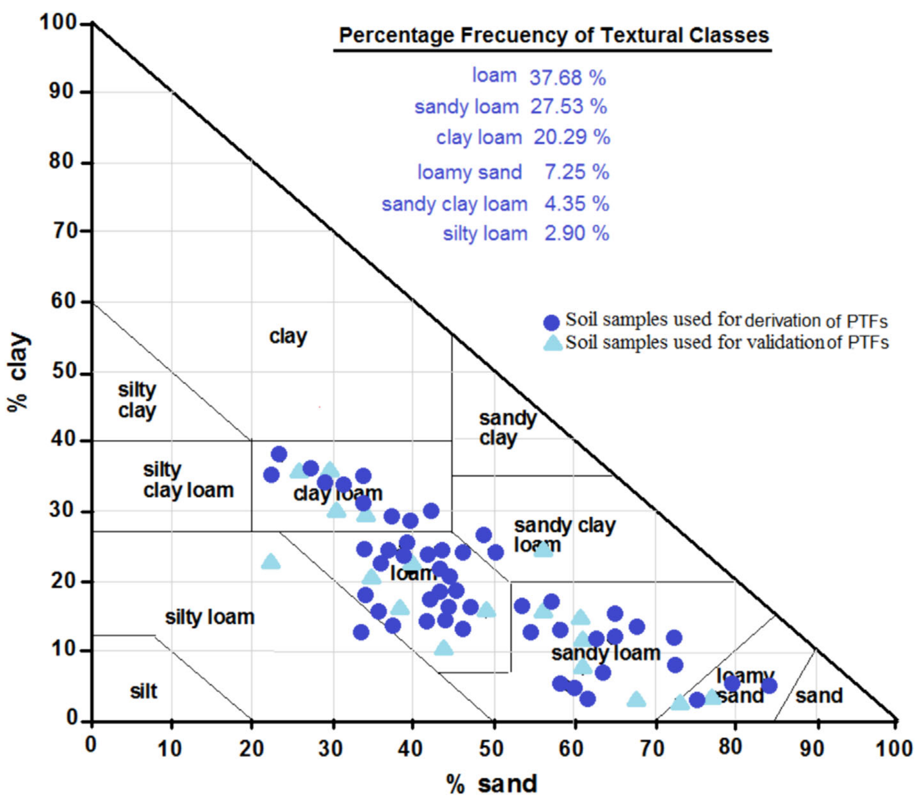

FIGURE 3 USDA soil texture triangle including the 69 sampling points.

where M_i and P_i are the individual *in situ* measured and predicted values of θ_{FC}, respectively; $\overline{M}$ is the mean of the measured *in situ* θ_{FC}; and n is the number of paired measured and predicted values. ME and RMSE are always positive, and a value of 0 indicates a perfect fit. A GMER equal to 1 corresponds to exact agreement between the measured and predicted data, whereas a GMER < 1 indicates that the predicted values are generally underestimated and that the GMER > 1 is overestimated (Wagner et al., 2001). The value of d' varies from 0 to 1, with higher values indicating better agreement between the measured and predicted values. In this study, following Li et al. (2013), the agreement between the measured and predicted values was considered excellent if NRMSE $< 10\%$, good if $10\% <$ NRMSE $< 20\%$, fair if $20\% <$ NRMSE $< 30\%$, and poor if NRMSE $> 30\%$.

3 | RESULTS AND DISCUSSION

3.1 | Soil characteristics

The statistics of the selected soil properties (texture, BD, SOC) of the 69 samples are presented in Table 2. The texture triangle of the soil samples is described in Figure 3. The samples were collected from agricultural lands. The soils used in this study cover a wide range of textures, ranging from clay loam to sandy loam, representing 6 out

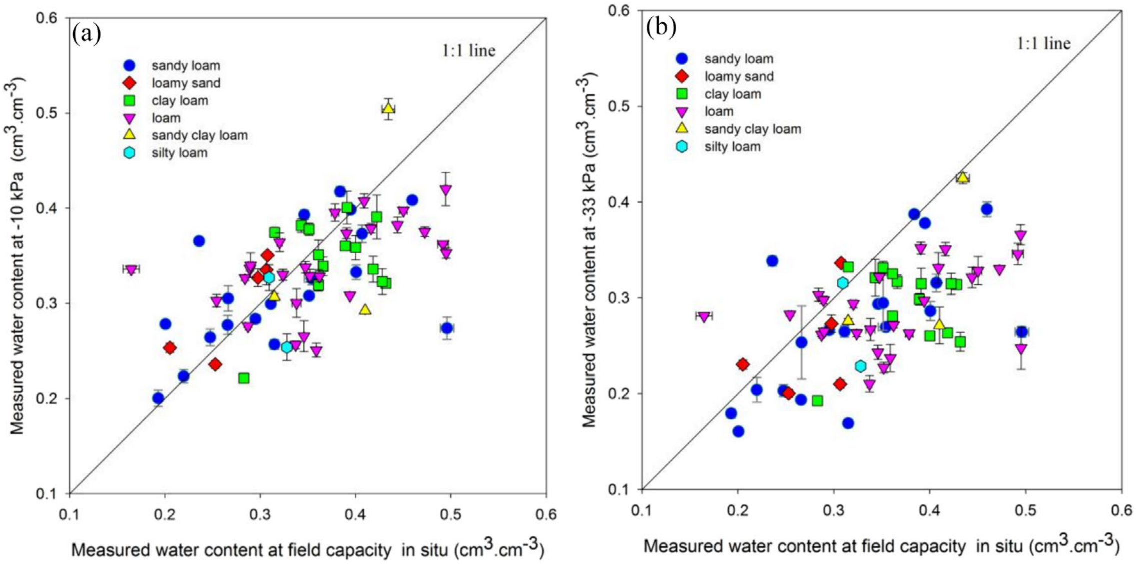

FIGURE 4 Comparison of water content at field capacity *in situ* with (a) water content at −10 kPa tension and (b) water content at −33 kPa tension (vertical and horizontal bars represent standard errors).

TABLE 3 Statistical comparison of θ_{FC} with θ_{33} and θ_{10}.

	RMSE (cm^3 cm^{-3})	GMER	NRMSE (%)	ME	D′
θ_{33}	0.11	0.81	30	−0.07	0.43
θ_{10}	0.08	0.95	22	−0.02	0.51

TABLE 4 Correlation matrix between selected soil properties.

	θ_{FC}	SOC	BD	Clay	Silt	Sand
θ_{FC}	1.00					
SOC	0.30*	1.00				
BD	0.01	−0.39**	1.00			
Clay	0.26*	−0.21	0.17	1.00		
Silt	0.35**	0.03	−0.40**	0.36**	1.00	
Sand	−0.37**	0.12	0.11	−0.85**	−0.80**	1.00

Note that:
*significant at $P < 0.05$.**significant at $P < 0.01$.

TABLE 5 Linear PTFs for estimating θ_{FC} using 75% of the soil samples and the corresponding RMSE.

	θ_{FC} (cm^3 cm^{-3})	RMSE (cm^3 cm^{-3})
Linear PTF-1	−0.0012 sand + 0.0018 clay + 0.3822	0.09
Linear PTF-2	−0.0013 sand + 0.0017 clay + 0.0022 SOC + 0.3811	0.09
Linear PTF-3	−0.0022 sand + 0.0018 SOC + 0.4491	0.08
Linear PTF-4	−0.0011 sand + 0.0019 silt + 0025 SOC + 0.3352	0.08
Linear PTF-5	−0.0012 sand + 0.0021 silt + 0.3350	0.08

of 12 texture classes. BD values are in the intermediate range, with a low standard deviation between sampling points. The value of SOC is low to extremely low, which is expected for desert conditions.

3.2 | Comparison of *in situ* measured θ_{FC} with laboratory measurements at −10 and −33 kPa

The laboratory measurements of θ_{10} and θ_{33} derived by using the suction plate were compared with the *in situ* measurements of θ_{FC} (Figure 4). Our findings summarized in Table 3 are that both θ_{10} and θ_{33} underestimate the *in situ* measured θ_{FC}, with larger discrepancies between θ_{33} and θ_{FC}. Although the correlation between the values is obvious, particularly between θ_{10} and θ_{FC}, the data points are mainly below the 1 : 1 line (which is lower for θ_{33} than for θ_{10}). Table 3 displays the statistical comparison between θ_{FC} and θ_{33} or θ_{10} using the indexes described in Section 2.5. The RMSE and NRMSE reveal that the estimates of θ_{FC} derived from θ_{10} are lower than those from θ_{33}. In addition, GMER is closer to 1 for θ_{10} than for θ_{33}, but in both cases, GMER is less than 1, indicating underestimation. Overall, θ_{10} was a better approximation of θ_{FC}, with MAEs, RMSEs and d' values of −0.02, 0.08 cm^3 cm^{-3}, and 0.51, respectively, whereas θ_{33} had MAEs, RMSEs and d' values of −0.07, 0.10 cm^3 cm^{-3}, and 0.43, respectively. This may suggest that for some soils, a tension lower than −10 kPa is needed. Importantly, these soils have low SOC contents; therefore, the results may vary for soils with high SOC contents.

We conclude that laboratory measurements of θ_{10} are more consistent with *in situ* measured θ_{FC} and therefore provide a more appropriate estimate for it in this study. Nevertheless, we could not find any consistent soil grouping, which suggests that θ_{33} provides a better fit, but this could be attributed to the low SOC of our tested soils. Notably, there are no heavy soils, such as clay or silty clay, in the soil samples (Figure 3). These results indicate that laboratory measurements of θ_{10} are more compatible with *in situ* measured θ_{FC} than θ_{33}.

θ_{FC} is influenced by many factors, such as soil texture and structure, clay type, and amount of SOM

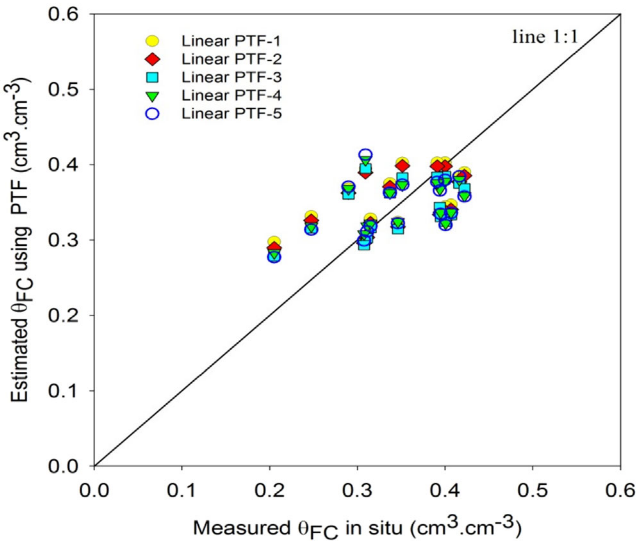

FIGURE 5 Measured θ_{FC} versus predicted θ_{FC} via the linear PTFs derived in this study.

TABLE 6 Performance of derived linear PTFs to estimate θ_{FC}.

	RMSE (cm^3 cm^{-3})	GMER	NRMSE (%)	d'
Linear PTF-1	0.05	1.03	15.04	0.46
Linear PTF-2	0.05	1.02	14.83	0.47
Linear PTF-3	0.05	0.99	14.88	0.46
Linear PTF-4	0.05	1.01	15.12	0.45
Linear PTF-5	0.05	1.01	15.25	0.47

TABLE 7 Nonlinear PTFs for estimating θ_{FC} using 75% of the soil samples and the corresponding RMSE.

	θ_{FC} (cm^3 cm^{-3})	RMSE (cm^3 cm^{-3})
Nonlinear PTF-1	$\varphi \times [0.511 + 0.096\,\text{clay}^{0.427}]$	0.09
Nonlinear PTF-2	$\varphi \times [0.600 + 0.016\,\text{clay}^{0.897}] \times \text{EXP}\left(\frac{0.446\,\text{sand}^{-7.918}}{\varphi}\right)$	0.09
Nonlinear PTF-3	$-0.013\,\varphi + 0.271\text{clay}^{0.094}$	0.07
Nonlinear PTF-4	$-0.176\,\varphi + 0.619\,\text{clay}^{-0.088} - 9.23 \times 10^{-7}\text{sand}^{2.834}$	0.07
Nonlinear PTF-5	$-0.189\,\varphi + 0.618\,\text{clay}^{-0.083} - 1.838 \times 10^{-6}\text{sand}^{2.68}$ $+1.384 \times 10^{-5}\text{SOC}^{7.517}$	0.07

(Rasoulzadeh & Yaghoubi, 2014; Santra et al., 2018). Therefore, θ_{FC} should be measured in the field to account for the complex dynamics of water in the soil (Hillel, 1998). Our results confirm that the conventional pressure-based approximation of field capacity at −10 and −33 kPa is inconsistent with the definition of field capacity because it does not ensure complete drainage from the soil (Hillel, 1998; Meyer & Gee, 1999).

3.3 | Correlations among the predictors

We correlated θ_{FC} with selected and easily measured soil properties. Field measurements of θ_{FC} revealed a significant correlation with the percentage of sand and silt at the 1% probability level and with the percentage of clay and SOC at the 5% probability level (Table 4). No significant correlation was found for BD at the 5% confidence level.

3.4 | Linear PTFs to estimate θ_{FC}

Various PTFs (Table 5) to estimate θ_{FC} were derived based on the proportions of sand, silt, clay, and SOC. Interestingly, the addition of BD did not improve the predictive capability of the PTFs. This may be attributed to the low variability in BD and SOC (Table 2).

To evaluate the performance of the derived linear PTFs (Table 5), 18 samples (25%) were randomly selected for validation (Figure 3), and the remaining samples were used for the development of the PTFs and subsequently compared with the measured θ_{FC} *in situ* (Figure 5).

As shown in Figure 5, all derived PTFs provide accurate and similar estimates of θ_{FC}. The statistical indexes shown in Table 6 indicate similar performance, with an NRMSE of approximately 15%, with slightly better results for linear PTF-2, which uses sand, clay and SOC as predictors. GMER showed that linear PTF-3 marginally underestimates θ_{FC}, whereas the other linear PTFs marginally overestimate it. Overall, PTF-1 is recommended if the SOC is not available. Although PTF-5 has the smallest RMSE, we do not recommend this model as it has the largest outlier. If the SOC is available, then linear PTF-4 is recommended for estimating θ_{FC}. Nevertheless, these PTFs need further validation with soils containing higher percentages of clay and SOM.

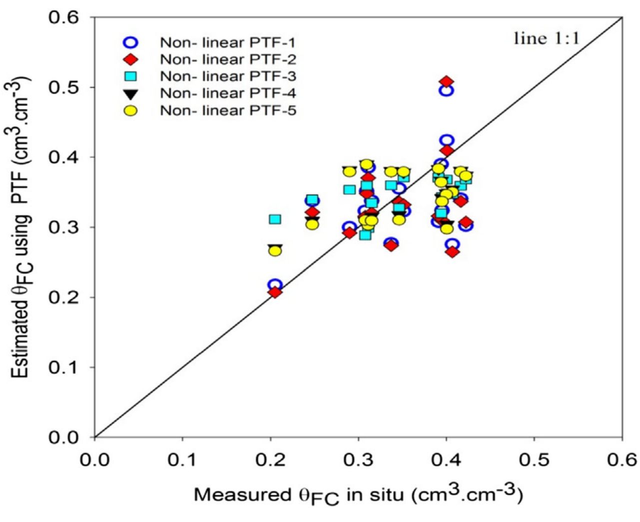

FIGURE 6 Measured θ_{FC} versus predicted θ_{FC} via the nonlinear PTFs derived in this study.

3.5 | Nonlinear PTFs to estimate θ_{FC}

The parameters of the selected nonlinear PTFs described in Table 7 are optimized by fitting to the *in situ* measured θ_{FC} using 75% of the soil samples.

To evaluate the performance of the derived nonlinear PTFs, 18 samples (25%) were randomly selected for validation (Figure 3). As in the previous case, the selected samples for validation were not used in the development of the nonlinear PTFs. The estimated values of θ_{FC} were calculated for the validation data set via the nonlinear PTFs listed in Table 7 and compared with the measured θ_{FC} *in situ* (Figure 6).

All derived nonlinear PTFs provide accurate estimates of θ_{FC}. The statistical indexes shown in Table 8 indicate good performance, with an NRMSE below 20%. The best performance in estimating θ_{FC} was obtained for nonlinear PTF-4, with an NRMSE < 15%. Nonlinear PTF-3 and nonlinear PTF-4 marginally overestimate θ_{FC}, whereas the other nonlinear PTFs marginally

TABLE 8 Performance of derived nonlinear PTFs to estimate θ_{FC} ($cm^3\ cm^{-3}$).

	RMSE ($cm^3\ cm^{-3}$)	GMER	NRMSE (%)	d'
Nonlinear PTF-1	0.07	0.97	19	0.44
Nonlinear PTF-2	0.07	0.95	19	0.48
Nonlinear PTF-3	0.05	1.00	15	0.34
Nonlinear PTF-4	0.05	1.01	15	0.47
Nonlinear PTF-5	0.05	0.99	15	0.47

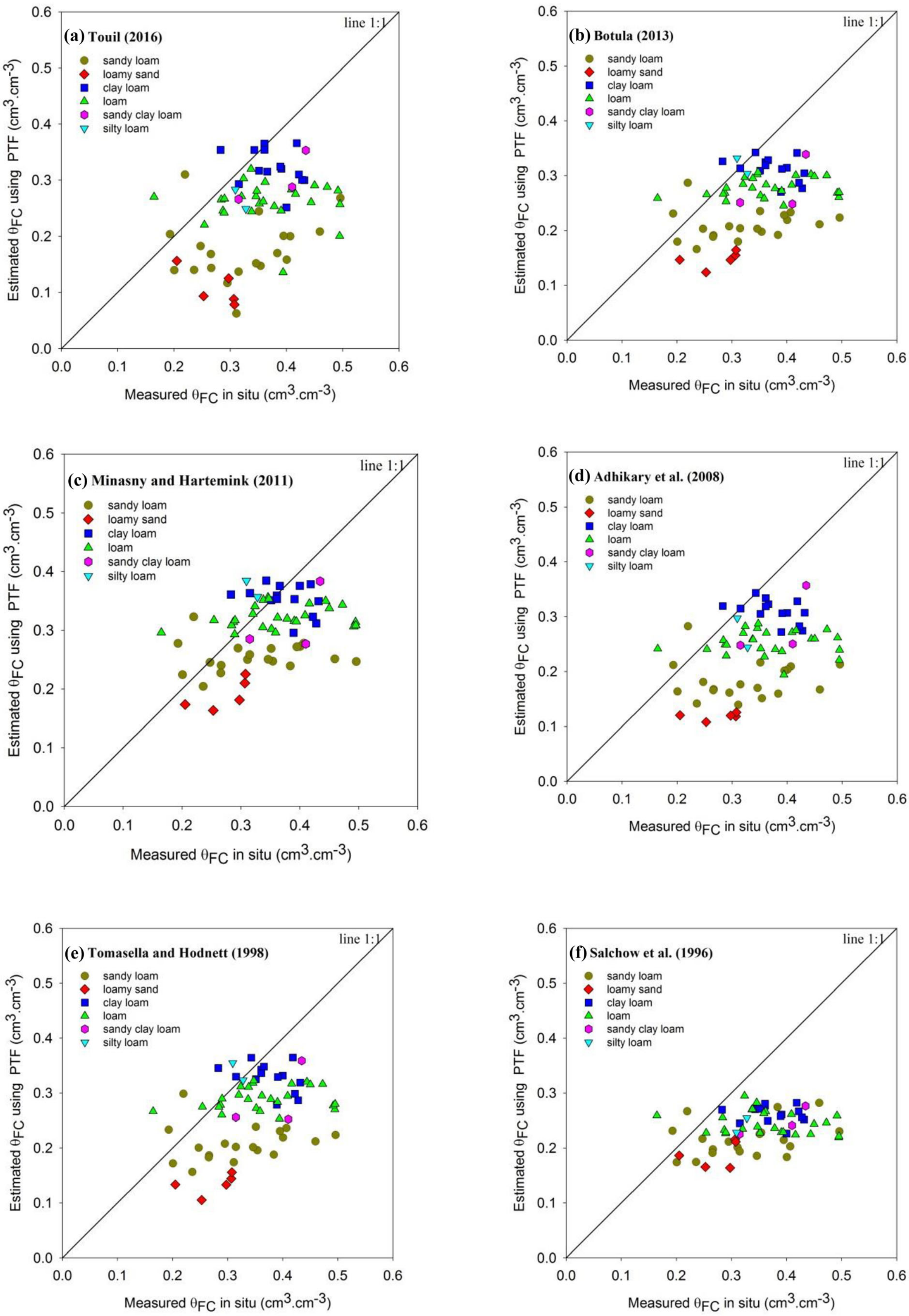

FIGURE 7 *In situ* measured θ_{FC} versus estimated values using different PTFs derived from the literature.

underestimate θ_{FC}. According to these results, simpler expressions with fewer parameters, such as nonlinear PTF-1 and nonlinear PTF-3, are recommended.

3.6 | Comparison with selected PTFs from the literature to estimate θ_{FC}

As mentioned, traditional PTFs estimate θ_{FC} based on the water content measured at −33 kPa under laboratory conditions. In this study, a set of six PTFs selected from the literature was compared with the *in situ* measured θ_{FC} value. Figure 7 shows the *in situ* measured θ_{FC} versus estimated values computed with selected PTFs. Most PTFs underestimate θ_{FC}. These results are expected because these PTFs were derived based on measurements at −33 kPa.

Nguyen et al. (2015) reported that Salchow et al. (1996) tended to underestimate the water content at −33 kPa because it was derived from coarse- and medium-textured soils. Therefore, the PTF of Salchow et al. (1996) did not perform well in estimating θ_{FC} with our soils which are predominantly fine-textured ones.

Considering that the distribution of pore size in soil is highly variable, caution should be taken when selecting a PTF. The accuracy of PTF estimation depends on the data set used to create them and may therefore not be applicable outside the region from which they were derived. The derived PTFs can potentially be used for regions having similar soils and management.

4 | CONCLUSIONS

Accurate estimates of θ_{FC} are crucial for agricultural and environmental applications. This study examined the validity of using measurements of water content at −10 or −33 kPa as an estimate for θ_{FC} by using a set of Iranian soils. The water content at −10 kPa provides more accurate estimates of *in situ* measured θ_{FC} for textures ranging from clay loam to sandy loam. However, water content measured at a lower tension than −10 kPa may fit better *in situ* measurements of θ_{FC}.

In the cold semi-arid regions of Iran, it is recommended that PTFs for estimating θ_{FC} use particle size distribution as a predictor, and slight improvement is obtained if SOC is used as a predictor. The usage of linear or nonlinear PTFs does not result in significant improvements in estimating θ_{FC} probably due to the low variability of the BD of the soil samples. The evaluation of the developed PTFs revealed satisfactory performance in the validation process. A consistent and standardized procedure to determine θ_{FC} is recommended because it constitutes a key variable for inferring soil water availability and air capacity.

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DATA AVAILABILITY STATEMENT

Data available on request from the authors.

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REFERENCES

Adhikary, P.P., Chakraborty, D., Kalra, N., Sachdev, C.B., Patra, A.K., Kumar, S., et al. (2008) Pedotransfer functions for predicting the hydraulic properties of Indian soils. *Australian Journal of Soil Research*, 46(5), 476–484. Available from: https://doi.org/10.1071/SR07042

Aschonitis, V.G., Antonopoulos, V.Z., Lekakis, E.H., Kotsopoulos, S.A. & Karamouzis, D.N. (2013) Estimation of field capacity for aggregated soils using changes of the water retention curve under the effects of compaction. *European Journal of Soil Science*, 64(5), 688–698. Available from: https://doi.org/10.1111/ejss.12058

Balland, V., Pollacco, J.A.P. & Arp, P.A. (2008) Modeling soil hydraulic properties for a wide range of soil conditions. *Ecological Modelling*, 219(3-4), 300–316. Available from: https://doi.org/10.1016/j.ecolmodel.2008.07.009

Botula, Y.D. (2013) *Indirect methods to predict Hydrophysical properties of soils of lower Congo*. Gent, Belgium: Ghent University, p. 236.

Colman, E.A. (1947) A laboratory procedure for determining the field capacity of soils. *Soil Science*, 63(4), 277–283. Available from: https://doi.org/10.1097/00010694-194704000-00003

Evett, S.R., Stone, K.C., Schwartz, R.C., O'Shaughnessy, S.A., Colaizzi, P.D., Anderson, S.K., et al. (2019) Resolving discrepancies between laboratory-determined field capacity values and field water content observations: implications for irrigation management. *Irrigation Science*, 37(6), 751–759. Available from: https://doi.org/10.1007/s00271-019-00644-4

Gee, G.W. & Or, D. (2002) Particle-size analysis. In: Dane, J.H. & Topp, G.C. (Eds.) *Methods of soil analysis. Part 4. Physical methods*. Madison, WI: Soil Science Society of America, Inc., pp. 255–294.

Grossman, R.B. & Reinsch, T.G. (2002) Bulk density and linear extensibility: Core method. In: Dane, J.H. & Topp, G.C. (Eds.) *Methods of soil analysis. Part 4. Physical methods*. Madison, WI: Soil Science Society of America, Inc., pp. 208–228.

Hillel, D. (1998) *Environmental soil physics*. San Diego, CA: Academic Press.

Huntington, T.G. (2007) Available Water Capacity and Soil Organic Matter. In: *Encyclopedia of soil science*, Second edition. New York: Taylor and Francis, pp. 139–143.

Inforsato, L. & de Jong Van Lier, Q. (2021) Polynomial functions to predict flux-based field capacity from soil hydraulic parameters. *Geoderma*, 404, 115308. Available from: https://doi.org/10.1016/j.geoderma.2021.115308

de Jong van Lier, Q. (2017) Field capacity, a valid upper limit of crop available water? *Agricultural Water Management*, 193, 214–220. Available from: https://doi.org/10.1016/j.agwat.2017.08.017

Kirkham, M.B. (2005) *Principles of soil and plant water relations 500 pp*. Amsterdam, San Diego, CA: Elsevier Academic Press.

Legates, D.R. & McCabe, G.J. (1999) Evaluating the use of 'goodness-of-fit' measures in hydrologic and hydroclimatic model validation. *Water Resources Research*, 35(1), 233–241. Available from: https://doi.org/10.1029/1998WR900018

Li, M.F., Tang, X.P., Wu, W. & Liu, H.B. (2013) General models for estimating daily global solar radiation for different solar radiation zones in mainland China. *Energy Conversion and Management*, 70, 139–148. Available from: https://doi.org/10.1016/j.enconman.2013.03.004

Libohova, Z., Seybold, C., Wysocki, D., Wills, S., Schoeneberger, P., Williams, C., et al. (2018) Reevaluating the effects of soil organic matter and other properties on available water-holding capacity using the National Cooperative Soil Survey Characterization Database. *Journal of Soil and Water Conservation*, 73(4), 411–421. Available from: https://doi.org/10.2489/jswc.73.4.411

Lyon, T.L. & Buckman, H.O. (1943) *The nature and properties of soils*, 4th edition, New York: MacMillan.

Meteorological organization. (2023) *Web site of Ardabil province meteorological*. Ardabil, Iran: Ardabil Meteorological Administration. Available from: https://ardmet.ir/en/

Meyer, P.D. & Gee, G. (1999) Flux-based estimation of field capacity. *Journal of Geotechnical and Geoenvironmental Engineering*, 125(7), 595–599. Available from: https://doi.org/10.1061/(ASCE)1090-0241(1999)125:7(595)

Minasny, B. & Hartemink, A.E. (2011) Predicting soil properties in the tropics. *Earth-Science Reviews*, 106(1-2), 52–62. Available from: https://doi.org/10.1016/j.earscirev.2011.01.005

Mingorance, M.D., Barahona, E. & Fernández-Gálvez, J. (2007) Guidelines for improving organic carbon recovery by the wet oxidation method. *Chemosphere*, 68(3), 409–413. Available from: https://doi.org/10.1016/j.chemosphere.2007.01.021

Nasta, P. & Romano, N. (2016) Use of a flux-based field capacity criterion to identify effective hydraulic parameters of layered soil profiles subjected to synthetic drainage experiments. *Water Resources Research*, 52(1), 566–584. Available from: https://doi.org/10.1002/2015WR016979

Nemes, A., Pachepsky, Y.A. & Timlin, D.J. (2011) Towards improving global estimates of field soil water capacity. *Soil Science Society of America Journal*, 75(3), 807–812. Available from: https://doi.org/10.2136/sssaj2010.0251

Nguyen, P.M., van Le, K., Botula, Y. & Cornelis, W.M. (2015) Evaluation of soil water retention pedotransfer functions for Vietnamese Mekong Delta soils. *Agricultural Water Management*, 158, 126–138. Available from: https://doi.org/10.1016/j.agwat.2015.04.011

Pollacco, J.A.P. (2008) A generally applicable pedotransfer function that estimates field capacity and permanent wilting point from soil texture and bulk density. *Canadian Journal of Soil Science*, 88(5), 761–774. Available from: https://doi.org/10.4141/CJSS07120

Pollacco, J.A.P., Fernández-Gálvez, J., Ackerer, P., Belfort, B., Lassabatere, L., Angulo-Jaramillo, R., et al. (2022) HyPix: 1D physically based hydrological model with novel adaptive timestepping management and smoothing dynamic criterion for controlling Newton–Raphson step. *Environmental Modelling & Software*, 153, 105386. Available from: https://doi.org/10.1016/j.envsoft.2022.105386

Rai, R.K., Singh, V.P. & Upadhyay, A. (2017) Irrigation scheduling. In: *Planning and evaluation of irrigation projects: methods and implementation*. Cambridge, MA: Academic Press. https://doi.org/10.1016/B978-0-12-811748-4.00012-1/-4

Rasoulzadeh, A. & Raoof, M. (2014) *Principals and methods of irrigation*, Second edition, Ardabil, Iran: Amidi Publisher, 286 pp. (in Persian).

Rasoulzadeh, A., Sepaskhah, A.R., Asghari, A. & Ghavidel, A. (2022) Long-term effects of barley residue managements on soil hydrophysical properties in North-Western Iran. *Geoderma Regional*, 30, e00552. Available from: https://doi.org/10.1016/j.geodrs.2022.e00552

Rasoulzadeh, A. & Yaghoubi, A. (2014) Inverse modeling approach for determining soil hydraulic properties as affected by application of cattle manure. *International Journal of Agricultural and Biological Engineering*, 7(2), 27–35.

Rawls, W.J. & Brakensiek, D.L. (1985) Prediction of soil water properties for hydrologic modelling. In: Jones, E.B. & Ward, T.J. (Eds.) *Proceedings of a symposium watershed Management in the Eighties*. American Society of Civil Engineers, New York, 30 April-1 May 1985, pp. 293–299.

Rawls, W.J., Pachepsky, Y.A., Ritchie, J.C., Sobecki, T.M. & Bloodworth, H. (2003) Effect of soil organic carbon on soil water retention. *Geoderma*, 166(1-2), 61–76. Available from: https://doi.org/10.1016/S0016-7061(03)00094-6

Reynolds, W.D. & Elrick, D.E. (2002) Constant head soil core (tank) method. In: Dane, J.H. & Topp, G.C. (Eds.) *Methods of soil analysis, part 4, physical methods. SSSA book series, 5*. Madison, Wisconsin: Soil Science Society of America, Inc., pp. 804–808.

Robertson, B.B., Almond, P.C., Carrick, S.T., Penny, V., Chau, H.W. & Smith, C.M.S. (2021) Variation in matric potential at field capacity in stony soils of fluvial and alluvial fans. *Geoderma*, 392, 114978. Available from: https://doi.org/10.1016/j.geoderma.2021.114978

Romano, N., Palladino, M. & Chirico, G.B. (2011) Parameterization of a bucket model for soil-vegetation-atmosphere modeling under seasonal climatic regimes. *Hydrology and Earth System Sciences*, 15(12), 3877–3893. Available from: https://doi.org/10.5194/hess-15-3877-2011

Romano, N. & Santini, A. (2002) Measurement of water retention: field methods. In: Dane, J.H. & Topp, G.C. (Eds.) *Methods of* *soil analysis, part 4*. Madison, WI: Soil Science Society of America, Inc., pp. 721–738.

Salchow, E., Lal, R., Fausey, N.R. & Ward, A. (1996) Pedotransfer functions for variable alluvial soils in southern Ohio. *Geoderma*, 73(3-4), 165–181. Available from: https://doi.org/10.1016/0016-7061(96)00044-4

Santra, P., Kumar, M., Kumawat, R.N., Painuli, D.K., Hati, K.M., Heuvelink, G.B.M., et al. (2018) Pedotransfer functions to estimate soil water content at field capacity and permanent wilting point in hot arid Western India. *Journal of Earth System Science*, 127(3), 35. Available from: https://doi.org/10.1007/s12040-018-0937-0

Tomasella, J. & Hodnett, M.G. (1998) Estimating soil water retention characteristics from limited data in Brazilian Amazonia. *Soil Science*, 163(3), 190–202. Available from: https://doi.org/10.1097/00010694-199803000-00003

Touil, S., Degre, A. & Chabaca, M.N. (2016) Sensitivity analysis of point and parametric pedotransfer functions for estimating water retention of soils in Algeria. *The Soil*, 2(4), 647–657. Available from: https://doi.org/10.5194/soil-2-647-2016

Turek, M.E., Armindo, R.A., Wendroth, O. & Dos Santos, I. (2019) Criteria for the estimation of field capacity and their implications for the bucket type model. *European Journal of Soil Science*, 70(2), 278–290. Available from: https://doi.org/10.1111/ejss.12747

Turek, M.E., van Lierb, Q.D.J. & Armindoc, R.A. (2020) Estimation and mapping of field capacity in Brazilian soils. *Geoderma*, 376, 114557. Available from: https://doi.org/10.1016/j.geoderma.2020.114557

Veihmeyer, F.J. & Hendrickson, A.H. (1931) The moisture equivalent as a measure of the field capacity of soils. *Soil Science*, 32(3), 181–194. Available from: https://doi.org/10.1097/00010694-19310900000003

Wagner, B., Tarnawski, V.R., Hennings, V., Müller, U., Wessolek, G. & Plagge, R. (2001) Evaluation of pedo-transfer functions for unsaturated soil hydraulic conductivity using an independent data set. *Geoderma*, 102(3-4), 275–297. Available from: https://doi.org/10.1016/S0016-7061(01)00037-4

Walkley, A. & Black, I.A. (1934) An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. *Soil Science*, 37(1), 29–38. Available from: https://doi.org/10.1097/00010694-193401000-00003

Will, G.M. & Stone, E.L. (1968) Pumice soils as a medium for tree growth. I. Moisture storage capacity. *New Zealand Institute of Forestry*, 13(1), 50–65.

Yi, X., Li, G. & Yin, Y. (2013) Comparison of three methods to develop pedotransfer functions for the saturated water content and field water capacity in permafrost region. *Cold Regions Science and Technology*, 88, 10–16. Available from: https://doi.org/10.1016/j.coldregions.2012.12.005

Zakizadeh Abkenar, F. & Rasoulzadeh, A. (2019) Functional evaluation of Pedotransfer functions for simulation of soil profile drainage. *Irrigation and Drainage*, 68(3), 573–587. Available from: https://doi.org/10.1002/ird.2328

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