POLISH JOURNAL OF SOIL SCIENCE
VOL. LIII/2 2020 PL ISSN 0079-2985

DOI: 10.17951/pjss/2020.53.2.225

FATEMEH MESKINI-VISHKAEE*, ALI REZA JAFARNEJADI*,
MOHAMMAD HADI MOUSAVI-FAZL*

EVALUATION OF SOIL PHYSICAL QUALITY IN DOMINANT SERIES OF CALCAREOUS SOILS IN SOUTH-WEST OF IRAN

Received: 09.12.2019
Accepted: 08.09.2020

Abstract. Calcareous soils are widely spread in arid and semiarid regions. Carbonates can affect soil quality by influencing soil pH, structure and soil available water. There are lots of calcareous soils in Iran and especially Khuzestan province, so providing sustainable agriculture evaluating the soil quality is essential. This study was done to evaluate the soil physical quality in dominant calcareous soil series in Khuzestan province, Iran. Soil physical quality indicators including Dexter's *S* index, air capacity, soil available water capacity, relative water capacity and macroporosity were calculated. The results showed that, based on Dexter's *S* index, only one calcareous soil series had a poor physical quality ($S < 0.035$). However, the simultaneous evaluation of different soil quality indicators showed that 56% and 22% of studied calcareous soil series had limited aeration and soil available water, respectively. While the weakest soil physical quality was related to the southeastern soil of Ahvaz, with both aeration and soil available water limitations. The results showed that the proper assessment of soil physical quality in calcareous soils requires considering more physical indicators than just Dexter's *S* index related to soil aeration condition including air capacity and macroporosity.

Keywords: aeration, macroporosity, soil available water, *S* index

* Soil and Water Research Department, Khuzestan Agricultural and Natural Resources Research and Education Center, Agricultural Research, Education and Extension Organization (AREEO), Ahvaz, Iran; corresponding author: arjafarnejady@gmail.com

INTRODUCTION

The physical quality of agricultural soils may be defined as the soil's strength and fluid conduction and storage specifications in the plant root zone (Topp *et al*. 1997, Reynolds *et al*. 2002, Reynolds *et al*. 2007) which in turn result from soil physical properties, climate, management practice, crop type and different soil-based chemical and biological processes (Reynolds *et al.* 2007). A soil with a good physical quality is able to maintain soil structure, establish plant, allow unrestricted root growth and resist erosion and compaction. So such soil with proper proportions of air, water, and dissolved nutrients is required to achieve both maximum crop performance and minimum environmental degradation (Topp *et al*. 1997, Reynolds *et al*. 2008, Drewry *et al*. 2008). The soil physical quality is effective with regard to the soil chemical and biological processes and hence its assessment is very important (Dexter 2004a).

The main concept of soil physical quality is to quantify land degradation and develop the best land management practices (Arshad and Martin 2002, Reynolds *et al*. 2007). The main steps to achieve these purposes include: 1) determining the soil physical properties as indicators of soil physical quality 2) establishing the optimal ranges or the upper and lower critical limits for each indicators and 3) evaluating the soil physical quality by comparing the calculated indicator values to optimal ranges and critical limits (Reynolds *et al*. 2008). Generally, soil quality indicators can be defined as soil properties that have the most sensitivity to changes in soil functions (Andrews *et al*. 2004), but should not be affected by short-term climatic patterns (Aparicio and Costa 2007).

Soil physical quality indicators contain useful information about the soil aeration and hydrological properties such as the bubbling pressure and the soil water retention capacity in the crop root zone (Lewandowski *et al.* 1999). Therefore, due to the effect of soil physical quality indicators on the volume and depth of plant rooting, they can effect on the soil nutrient availability and subsequently plant growth. Some of the most important indicators of physical quality include relative field capacity, plant available water, air capacity, macroporosity, bulk density, organic carbon content and structural stability index (Topp *et al.* 1997, Reynolds *et al.* 2007, Reynolds *et al.* 2009, Ghiberto *et al.* 2015). Soil structure conditions influence the pore-size distribution that can be described by means of the soil moisture retention curve (SMRC) which in pores draining up to the inflection point are structural pores (Dexter 2004a). Hence, Dexter (2004a) proposed an S index at inflection point of SMRC. This index relates to main soil properties including soil hydraulic conductivity, compaction, soil water retention, penetration resistance, root growth and soil structural stability (Gate *et al.* 2006, Dexter and Czyz 2007, Dexter and Richard 2009).

Soil physical degradation generally results in a reduction in structural attributes including pore geometry and continuity (Lal 2015). Hence, all proposed indicators are either direct or indirect expressions of state and/or function of soil pore space (Reynolds *et al*. 2009, Ghiberto *et al*. 2015). Accordingly, Reynolds *et al*. (2009) proposed an optimal pore size distribution by using various soil physical quality indicators to study different combinations of soil management practices. In addition, they quantified pore distribution curves by mode, mean, median, skewness, dispersion and kurtosis.

The Khuzestan province plays an important and strategic role in the agricultural production of Iran (with 2.8 million ha of arable lands). Moreover, the Khuzestan province, because of arid and semi-arid climate, has highly fragile ecosystems that are characterized by low soil fertility, high organic matter decomposition rates, limited soil aeration, limited water availability (Solomon *et al.* 2000, Austin and Vivanco 2006). In recent years, due to intensive cultivation, no crop rotation, inappropriate management of soil and water resources, and the occurrence of drought, has deteriorated soil and water resources and hence crop production (Jafarnejadi *et al*. 2019). Intensive field-crop production can cause the physical quality of agricultural soils to decline (Reynolds *et al.* 2002). Declined soil physical quality linked to decreasing crop performance or profitability, as well as negative environmental impacts such as wind or water erosion and the leaching of pesticides and soil nutrients into surface and ground waters (Wallace and Terry 1998). In addition, Calcareous soils are widespread throughout Iran, especially in the Khuzestan province. Carbonates as a cementing agent, affect the soil physical properties by secondary sand formation and silt-sized granules that mimic primary particles, which affects soil structure and pedogenic development by controlling the infiltration and aeration rates (Kishchuk 2000). An assessment of soil quality can be helpful for optimum production and natural resources conservation. Therefore, this study was conducted to quantify the soil physical quality in the dominant series of calcareous soils in the Khuzestan province, Iran. Accordingly, the objectives of this study were to i) evaluate some soil properties of dominant series of calcareous soils in the Khuzestan province, ii) quantify physical quality of studied calcareous soil series using various indicators and iii) use some parameters to propose optimal pore distribution curve relevant to soil physical quality in calcareous soil series.

MATERIALS AND METHODS

According to some soil properties, including soil salinity, texture, lime content and gypsum, about 20 soil series have been identified in the Khuzestan province. Based on soil classification, the main soil orders of Khuzestan province were Entisols, Aridisols and Inseptiosols. From 20 calcareous soil series in Khuzestan province, nine dominant calcareous soil series were selected. For each soil series, five pairs of soil samples from depth of 0–20 cm (disturbed and undisturbed) were collected and translocated to the laboratory. The soil organic carbon was measured using oxidation (Walkley and Black 1934). Total neutralizing (TNV) was determined by acid neutralization, soil texture and bulk density were measured using a hydrometer and a sieve (Gee and Or 2002) and a cylinder (Grossman and Reinsch 2002), respectively. To determine the soil water characteristic curve (SWRC), first the samples were saturated with a calcium chloride solution of 0.01 normal, and moisture content were determined using a hanging water column (in a suction of 10 to 150 cm), a pressure plate (in suction 300 to 1,000 cm) and pressure membrane (in suction 1,000 to 15,000 cm) (Dane and Hopmans 2002). Then, using the RETC software, van Genuchten (1980) equation (Eq. 1) was fitted to the measured soil water characteristic curve data.

$$\theta = \theta_r + \frac{\theta_s - \theta_r}{\left[1+(\alpha h)^n\right]^{\left[1-\frac{1}{n}\right]}} \tag{1}$$

where: θ_r and θ_S are the residual and saturation soil moisture content (cm^3 cm^{-3}), h is soil matric head (cm), α (cm^{-1}), and n(-) are the shape parameters of SWRC. Because of loamy to clay texture of main soil series in the Khuzestan province, soil moisture content at suction heads of 330 and 15,000 cm were used as the field capacity (FC) and permanent wilting point (PWP), respectively.

Soil physical quality indicators

From the curve indicators suggested by Reynolds *et al.* (2002), Dexter (2004a), and Reynolds *et al.* (2009), namely S index, air capacity (AC), plant-available water capacity (PAW), relative water capacity (RWC), macroporosity (P_{Mac}) and pore-size distribution curve were determined. The soil physical quality parameters considered are indicators of soil water storage, soil air storage, and impedance to root growth (Reynolds *et al.* 2002). Although the above soil physical quality indicators and their optimal ranges or critical limits have been described elsewhere (e.g. Reynolds *et al.* 2002, Dexter 2004a, Reynolds *et al.* 2009), brief "working definitions" will be repeated here for completeness and the reader's convenience.

Dexter's S index

The slope of the SWRC at the inflection point is Dexter's *S* index (equation 2), which can be estimated using the parameters of the van Genuchten model by fitting equation 1 to the SWRC data (Dexter 2004a):

$$S = -n(\theta_{sg} - \theta_{rg})\left[\frac{2n-1}{n-1}\right]^{(\frac{1}{n}-2)} \tag{2}$$

where: θ_{rg} and θ_{Sg} are the soil residual and saturation gravimetric moisture contents (kg kg^{-1}), respectively, which were calculated by dividing the volumetric moisture into the bulk density of each soil. Although *S* is always negative, the absolute value of *S* was presented and discussed in this study. Soil physical quality based on *S* index is divided into four groups including very poor (0.020 > *S*), poor ($0.020 \leq S < 0.035$), good ($0.035 \leq S < 0.050$) and very good ($S \geq 0.050$) soil physical or structural quality (Dexter 2004a). It should be mentioned that no conclusions can be drawn about the physical quality of a soil just by knowing its *S* index value (de Jong van Lier 2014).

Air capacity

Soil air capacity (AC, cm^3 cm^{-3}) is often useful indicator of soil aeration. This indicator was calculated by equation (3) (White 2006):

$$AC = \theta_S - \theta_{FC} \;\; ; \; 0 \leq AC \leq \theta_S \tag{3}$$

where: θ_{FC} is the soil moisture content at field capacity (cm^3 cm^{-3}). Wesseling and van Wijk (1957) showed that the diffusion of gases in the soil when aeration porosity is less than 0.10 cm^3 cm^{-3} is stopped. Therefore, the roots of plants require at least 0.10 cm^3 cm^{-3} aeration porosity to survive (Kirkham 2005).

Plant water available

The third studied physical soil quality indicator is the plant available water (PAW). PAW (cm^3 cm^{-3}) is defined as the ability of the soil for water storage that can be used for plant roots. Veihmeyer and Hendrickson (1927) defined the PAW indicator as the soil moisture content maintained between field capacity (FC) and the permanent wilting point (PWP) (equation 4):

$$PAW = \theta_{FC} - \theta_{PWP} \; ; \; 0 \leq PAW \leq \theta_{FC} \tag{4}$$

The PAW ≥ 0.20 cm^3 cm^{-3} is considered as "excellent" for maximum root growth (Cockroft and Olsson 1997), $0.15 \leq PAW < 0.20$ cm^3 cm^{-3} – as "good" condition, $0.10 \leq PAW < 0.15$ cm^3 cm^{-3} – as "limited" condition and PAW < 0.10 cm^3 cm^{-3} – as "weak and dry" condition (Warrick 2002, White 2006).

Relative water capacity

Relative water capacity (RWC) is a dimensionless soil physical quality indicator and shows the soil's capacity to store water and air relative to the total pore volume of soil (Reynolds *et al*. 2008):

$$RWC = \left(\frac{\theta_{FC}}{\theta_S}\right) = \left[1 - \left(\frac{AC}{\theta_S}\right)\right];\ 0 \le \text{RWC} \le 1 \tag{5}$$

When 0.6 ≤ RWC ≤0.7, the optimal balance between soil water capacity and soil air capacity in the root zone may occur in which maximize the microbial production of nitrate (main nutrient determines the plant growth and yield) (Doran *et al*. 1990). Lower or higher values of RWC (RWC < 0.6; RWC > 0.7) result in reduced microbial activity due to insufficient soil water and air contents, respectively (Skopp *et al*. 1990).

Macroporosity

The last physical quality indicator was to determine the soil macroporosity (P_{mac}). This indicator was calculated using equation (6) (Dexter and Czyz 2007).

$$P_{mac} = \theta_s - \theta_m;\ 0 \le P_{mac} \le \theta_s \tag{6}$$

where: θ_m is the saturation volumetric moisture content in the soil matrix exclusive of macropores and equal to the soil moisture content at the suction head of 10 cm. In medium- to fine-textured soils, P_{mac} values are in range of 0.05–0.10 $cm^3\ cm^{-3}$ when un-degraded, and $P_{mac} < 0.04\ cm^3\ cm^{-3}$ when degraded by compaction or consolation (Drewry *et al*. 2001, Drewry and Paton 2005).

In this study, the moisture corresponding to FC and PWP at suction heads of 330 and 15,000 cm, respectively, were used to calculate soil physical quality indicators (Moncada *et al*. 2014). Most studies assume that FC as the soil moisture at a constant matric head (100 or 330 cm) to calculate soil physical indicators (Arshad and Martin 2002, Reynolds *et al.* 2009, Moncada *et al*. 2014). However, this definition of the FC is not agreed upon universally by all researchers (Groenevelt *et al*. 2001) and different *h*-values are ascribed to the FC for different soil textures (Minasny and McBratney 2003). Whereas FC is not actually a constant soil moisture and, indeed it is the soil moisture at which the soil drainage flux becomes negligible (Cassel and Nielsen 1986). Subsequently, the head-based definition of FC as the common method of estimating FC is at odds with the flux-based interpretation because, there is no guarantee that the soil moisture at h = 330 cm (or 100 cm) results in a negligible drainage rate (Meyer and Gee 1999). Several and often arbitrary values have been proposed as the negligible flux at the FC (e.g. 0.05 mm day^{-1} by Nachabe [1998] and 0.1 mm day^{-1} by Twarakavi *et al.* [2009]). Due to lack of physically-based link between these arbitrary head values and the negligible flux at the FC, concept of FC remains problematic (Assouline and Or 2014, Meskini-Vishkaee *et al.* 2018). Moreover, despite these attempts to examine FC as dynamic, these theoretical analyses do not include plants (Logsdon 2019). The descriptive statistics were determined using SPSS v19 software and fitting the van Genuchten equation (1) on the measured soil water curve characteristics using RETC software.

Pore volume distribution function

The pore volume distribution function was evaluated as suggested by Reynolds *et al*. (2009), hence the "normalized" pore volume distribution function $S^*(h)$ (dimensionless), was determined by plotting the slope of the soil moisture curve expressed as the volumetric water content θ_v(cm^3 cm^{-3}), versus ln(h), against equivalent pore diameter d_e(μm), on a $\log_{10}$ scale (e.g. Jena and Gupta 2002):

$$S^*(h) = \frac{S_v(h)}{S_{vi}} \tag{7}$$

$$d_e = \frac{2980}{h} \tag{8}$$

where: S_v (h) is the slope of the θ (h) vs. ln(h) function, and S_{vi} is the slope at the inflection point of the SMC. The pore volume distribution was also characterized and compared using location and shape parameters (Blott and Pye 2001), where the location parameters included the mode, median, and mean d_e values and shape parameters included standard deviation (SD), skewness and kurtosis. The median d_e (d_{median}) occurs at a degree of saturation of 0.5, and the modal d_e (d_{mode}) corresponds to the relative water content or matric potential at the SWRC inflection. The d_{mode} also defines the most frequently occurring d_e value in the pore volume distribution. The details on the derivation of location and shape parameters can be found in Reynolds *et al*. (2009).

RESULTS AND DISCUSSION

Some soil physical and chemical properties are shown in Table 1. The results showed that, except three series (Ramhormoz-Rostamabad – 2, Khorramshahr – 2 and Ahvaz-Hamidieh), all main calcareous soils in the Khuzestan province had loam texture. The lowest and the highest values of soil salinity were observed in Ramhormoz-Rustamabad (5th studied soil series, 2.43 dS.m^{-1}) and south-west of Ahvaz (the first soil series, 47 dS.m^{-1}), respectively.

Table 1. Some soil physical and chemical properties in dominant series of calcareous soils

Soil series \ Characteristics	Location	Texture	pH (-)	EC ($dS.m^{-1}$)	Sand (%)	Clay (%)	TNV (%)	Bd (g cm^{-3})
1	Ahvaz-South	Loam	7.1	33.4	40	22	52	1.52
2	South-West Ahvaz	Loam	7.3	47	32	24	54	1.14
3	Ramhor-moz-Bazidi	Loam	7.6	4.6	26	28	60	1.41
4	Ramhor-moz-Rostam-abad	Loam	7.2	6.0	30	20	50	1.22
5	Ramhor-moz-Rostam-abad	Silty clay loam	7.5	2.4	14	36	52	1.12
6	Shadegan	Loam	7.5	7.6	28	24	50	1.23
7	Khorramshar	Loam	7.6	17	28	26	49	1.2
8	Khorramshar	Clay	7.4	19.5	24	44	50	1.4
9	Ahvaz-Hamid-eyeh	Silty clay Loam	7.3	5.7	18	39	48	1.25

pH – soil reaction, EC – electrical conductivity, TNV – total neutralizing value, Bd – bulk density

The descriptive statistics of the parameters of van Genuchten model (Eq. 1) fitted to the soil water characteristic curve in the studied soil series were presented in Table 2. The range of the van Genuchten experimental parameters values (*α* and *n*) indicated the proper variety of soil water characteristic curves in the studied soil samples.

Table 2. The descriptive statistics of van Genuchten experimental parameters (Eq. 1) and soil moisture contents at field capacity and permanent wilting point

Parameters	van Genuchten experimental parameters				FC	PWP
	α (cm^{-1})	n (-)	θ_r (cm^3 cm^{-3})	θ_s (cm^3 cm^{-3})	(cm^3 cm^{-3})	(cm^3 cm^{-3})
Mean	0.10	1.249	0.024	0.564	0.404	0.229
Minimum	0.0063	1.097	0	0.421	0.317	0.166
Maximum	0.2529	2.040	0.219	0.714	0.564	0.265

α and *n* – van Genuchten experimental parameters; θ_r – residual soil moisture; θ_s – saturation soil moisture; FC – field capacity; PWP – permanent wilting point

Assessment of soil physical quality based on different indicators

The values of different soil physical indicators in the main calcareous soils series of the Khuzestan province were shown in Table 3. The mean of Dexter's

S index in the main calcareous soils series of the Khuzestan province was 0.05. The lower values of *S* index were considered to correspond to a loss of structural pores and degradation in soil structure (Kechavarzi *et al*. 2010). The lowest and highest values of Dexter's *S* index were observed in soil samples of Shadegan (0.031) and south of Ahvaz (0.101), respectively (Table 3). These results confirmed using the reported range of *S* index in agricultural soils (0.007 > *S* > 0.14) by Dexter and Czyz (2007). Based on Dexter's *S* index, the soil quality of Shadegan series was poor (*S* < 0.035), while south-east Ahvaz, Ramhormoz-Bazidi, Ramhormoz-Rostamabad (the 4th soil series), Ramhormoz-Rostamabad (the 5th soil series) and Khorramshahr (the 7th soil series) had good soil physical quality (0.035 < *S* < 0.05). Soil samples from south Ahvaz, Khorramshahr (the 8th soil series) and Ahvaz-Hamidieh had very good physical quality (*S* > 0.05). Accordingly, almost 90% of studied main calcareous soils series had good to very good physical quality (*S* > 0.035).

Table 3. The values of different indicators of soil physical properties in main calcareous soils series of the Khuzestan province

Physical quality index / Soil series	Dexter's *S* index (-)	AC (cm^3 cm^{-3})	PAW (cm^3 cm^{-3})	RWC (-)	P_{mac} (cm^3 cm^{-3})
South Ahvaz (1)	0.101	0.225	0.159	0.630	0.0007
South-east Ahvaz (2)	0.036	0.105	0.134	0.751	0.0576
Ramhormoz-Bazidi (3)	0.043	0.215	0.165	0.656	0.0310
Ramhormoz-Rostamabad (4)	0.049	0.166	0.177	0.674	0.0877
Ramhormoz-Rostamabad2 (5)	0.035	0.19	0.119	0.649	0.0500
Shadegan (6)	0.031	0.188	0.102	0.649	0.0592
Khorramshar (7)	0.044	0.098	0.189	0.814	0.00373
Khorramshar (8)	0.065	0.150	0.305	0.790	0.00450
Ahvaz-Hamideyeh (9)	0.053	0.100	0.222	0.830	0.00340

AC – aeration porosity; PAW – plant water available; RWC – relative water capacity; P_{mac} – coarse pore

Based on the air capacity indicator, three soil series (Khorramshahr [7], Ahvaz-Hamidieh and south-east Ahvaz) had the lowest values of aeration porosity, while the highest air capacity indicator was observed in south Ahvaz and Ramhormoz-Bazidi soil series. However, the air capacity indicator in the 7th soil series (Khorramshahr) reached less than the critical limit (AC < 0.1 cm^3 cm^{-3}). Therefore, based on the air capacity indicator, about 90% of the studied soil series had a good aeration quality. The results of Table 3 were shown that the least value of plant available water (PAW) was observed in Shadegan series (0.102 cm^3 cm^{-3}). While the 8th soil series (Khorramshahr) had the highest value of PAW (30.5 cm^3 cm^{-3}). Based on the PAW indicator, 33% of the studied soil series (south-east Ahvaz, Ramhormoz-Rustamabad [5] and Shadegan) were classified in the limited physical quality (0.10 ≤ PAW < 0.15 cm^3 cm^{-3}), 44% (south Ahvaz, Ramhormoz-Bazidi, Ramhormoz-Rustamabad [4] and Khorramshahr

[7]) were in good physical quality ($0.15 \leq PAW < 0.20$ cm^3 cm^{-3}) and 23% (Khoramshahr [8] and Ahvaz-Hamidieh soil series) had the ideal physical quality ($PAW \geq 0.20$ cm^3 cm^{-3}) for maximum root growth. The least and the highest values of relative water capacity indicator (RWC) were observed in the south Ahvaz (0.63) and Ahvaz-Hamidiyeh (0.83), respectively (Table 3). About 56% of the studied soil series were in the optimum range of RWC ($0.6 \leq RWC \leq 0.7$). Therefore, only 56% of the main calcareous soil series of the Khuzestan province had *n* suitable balance between the soil moisture and aeration capacity in the root zone so that maximize the microbial production of nitrate (Table 3). The soil series consisted of south-east Ahvaz, Khorramshahr (7), Khorramshahr (8) and Ahvaz-Hamidyeh had an RWC value of more than 0.7, which confirmed the lack of soil moisture in the root zone that limited the microbial production of nitrate (Skopp *et al*. 1990). In addition, the results of Table 3 showed that the macroporosity indicator (P_{mac}) in about 50% of the studied soil series (south Ahvaz, Ramhormoz-Bazidi, Khorramshahr [7], Khorramshahr [8] and Ahvaz-Hamidieh) was less than the critical limit ($P_{mac} = 0.04$ cm^{3}cm^{-3}). Based on the soil physical quality indicators and their optimal limits, the main calcareous soils series of the Khuzestan province can be organized into four groups (Table 4).

Table 4. Grouping main calcareous soils series in the Khuzestan province based on soil physical properties

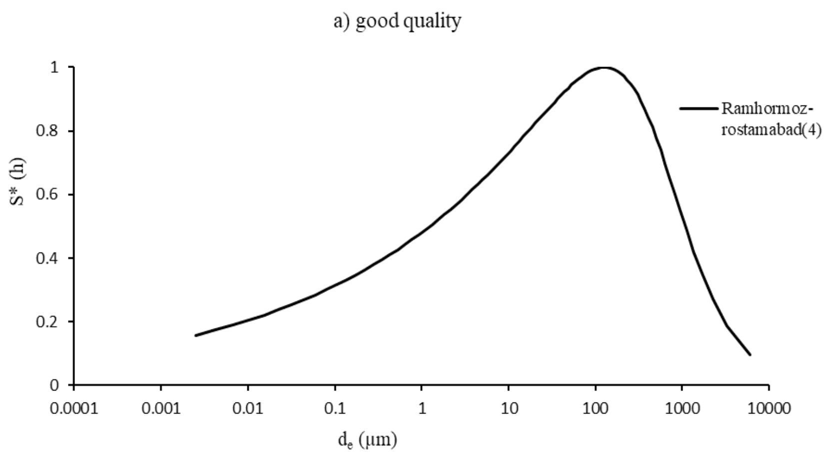
Group	Group 1	Group 2		Group 3	Group 4
Soil physical index	PAW > 0.15 AC > 0.1	PAW > 0.15 AC < 0.1	PAW > 0.15 AC > 0.1 $P_{mac} < 0.04$	PAW < 0.15 AC > 0.1	PAW < 0.15 AC < 0.1
Soil series	Ramhormoz- -Rostamabad (4)	Khorramshar (7) Ahvaz- -Hamideyeh	Ahvaz-South Ramhormoz- -Bazidi Khoramshar (8)	Ramhormoz- -Rostamabad (5) Shadegan	south-east Ahvaz

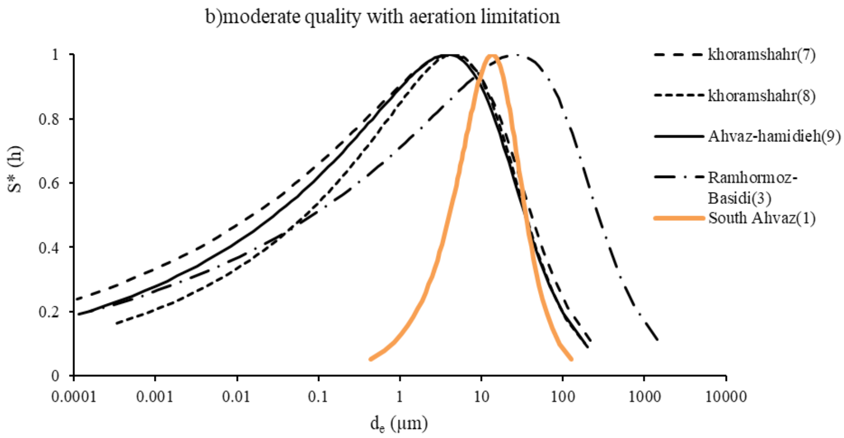
AC – aeration porosity; PAW – plant water available; P_{mac} – macropores

Group 1 consisted of the 4th soil series (Ramhormoz-Rostamabad) in which all the studied indicators fell within their respective optimal ranges, i.e. AC was above the 0.14 m^3 m^{-3} minimum (0.166 m^3 m^{-3}), PAW was good (0.177 m^3 m^{-3}), RWC was between 0.6 and 0.7 (0.674), P_{mac} was above the 0.07 m^3 m^{-3} (0.087 m^3 m^{-3}) and *S* index indicated "good" structural quality (0.049) (Table 3) and had no limitation of the aeration and soil water availability. Therefore, this soil series was considered "preferred" with respect to overall soil physical quality. Group 2 of soil series contained suitable water, but with limited aeration, which included southern Ahvaz, Ramhormoz-Basidi, Khorramshahr (7), Khorramshahr (8) and Ahvaz-Hamidieh series. It should be mentioned that this group can be divided into two subgroups. The first subgroup included soils with aeration porosity less than the critical limit and the second subgroup included the studied soils from the southern Ahvaz, Ramhormoz-Bazidi and Khorramshahr (8), which despite optimal aeration porosity (AC > 0.1 cm^3 cm^{-3}), the values of the coarse pore diameter were less than the critical limit (P_{mac} < 0.04 cm^3 cm^{-3}). The macroporosity indicator is the volume of macro pores (pores with a diameter greater than 0.3 mm), indicating the soil ability to water drainable, growth and root penetration (Reynolds *et al.* 2009). The macroporosity of the soil series in second subgroup was probably destroyed due to applying the incorrect management, burning plant residual, using no crop rotations and subsequently, increasing soil bulk density (1.4–1.52 g cm^{-3}, Table 1). In agricultural soils, tillage practices modify soil properties and quality and hence affect crop production and the environment (Batey and McKenzie 2006). Machinery traffic, tillage and loss of soil organic matter have adverse effects on soil structural quality (Guimaraes *et al*. 2013) and are generally resulting in soil compaction (Batey 2009). Soil bulk density is an indirect indicator of aeration, soil mechanical strength and soil's ability to save and transfer water (Reynolds *et al*. 2008), several studies have shown that in soils with moderate to heavy texture, the optimum range of soil bulk density for maximum producing is 0.9–1.2 g cm^{-3} (Reynolds *et al.* 2007, Tormena *et al.* 2008, Drewry *et al*. 2008). The results obtained by Shekofteh *et al*. (2018) showed that soil bulk density is the most important property affecting the soil physical quality indicators. The third group consisted of Ramhormoz-Rustamabad (5) and Shadegan soil series with suitable aeration and low soil water availability. Finally, the fourth group included south-west Ahvaz soil series which had both aeration and soil available water restrictions (Table 4).

Comparison of the different groups of soil physical quality shown in Table 4 confirmed the complexity of soil structure and the risk of evaluating soil quality based only on an indicator (such as *S* index). Based on Dexter's *S* index, the variation of soil physical quality in main calcareous soil series of the Khuzestan province were in the following order: south Ahvaz > Khorramshahr (8) > Ahvaz-Hamidiyeh > Ramhormoz-Rustamabad (4) > Khorramshahr (7) > Ramhormoz-Bazidi > south-east of Ahvaz > Ramhormoz-Rustamabad (5) > Shadegan (Table 3). Considering all soil physical quality indicators it was shown that Ramhormoz-Rustamabad (4) had the best physical soil quality in the studied soil series, whereas three other soil series (south Ahvaz, Khorramshahr [8] and Ahvaz-Hamidyeh) with higher S index than Ramhormoz-Rustamabad (4) and high soil available water (0.159 < PAW < 0.222 m^3 m^{-3}), had aeration and drainage limitations due to incorrect cropping management, high soil bulk density and low macroporosity (Table 4). The results showed that Dexter's *S* index is more emphasized on the soil available water in assessing the soil physical quality, hence the assessment of the soil physical quality for soils with limitations of aeration and/or drainage rate based only on *S* index may be associated with the wrong judgment. As shown in Dexter (2004b), *S* index is related to the sharpness of the pore-size distribution which is indicative of the presence of microstructure. Of course, it should be noted that three soil series with the weakest physical soil quality based on all the studied indicators (Ramhormoz-Rustamabad [5], Shadegan and south-east of Ahvaz) also had the lowest values of Dexter's *S* index. In fact, in the three soil series, Dexter's *S* index was less than or equal to the critical limit of the Dexter's *S* index ($S \leq 0.035$), which confirmed the ability of this index to determine the poor soil physical quality. So, using *S* index alone is not enough to evaluate the proper physical quality in calcareous soil series of the Khuzestan province. The value of $S = 0.035$ has been questioned by de Jong van Lier (2014) and Reynolds *et al*. (2009) because of its inconsistent designations of soil physical quality and a lack of consistency with other physical indicators. The use of Dexter's *S* index as an indicator to be considered as part of a minimum data set of soil physical quality indicators assessment is less viable when other indicators such as bulk density and porosity are much more easily determined and more consistent than *S* index (Moncada *et al.* 2014). Consequently, the critical limit proposed by Dexter (2004a) as a discriminating threshold of soil degradation problems does not appear to be applicable for all soil types or under all conditions of management and should be used judiciously and in relation to other indicators for assessing soil quality, Meskini-Vishkaee and Mirkhani (2019) also confirmed these findings. Their results on 35 samples of the Alborz province in Iran showed that the use of Dexter's *S* index, regardless of other indicators, caused a 10% error in evaluating the physical quality of the studied soils.

After grouping the main soil calcareous series of the Khuzestan province, the pore-size distribution curves were plotted for each group (Fig. 1). In addition, the statistical parameters of these curves, including mean, mode and medianas well as curve shape parameters (kurtosis, skewness and standard deviation) are presented in Table 5.





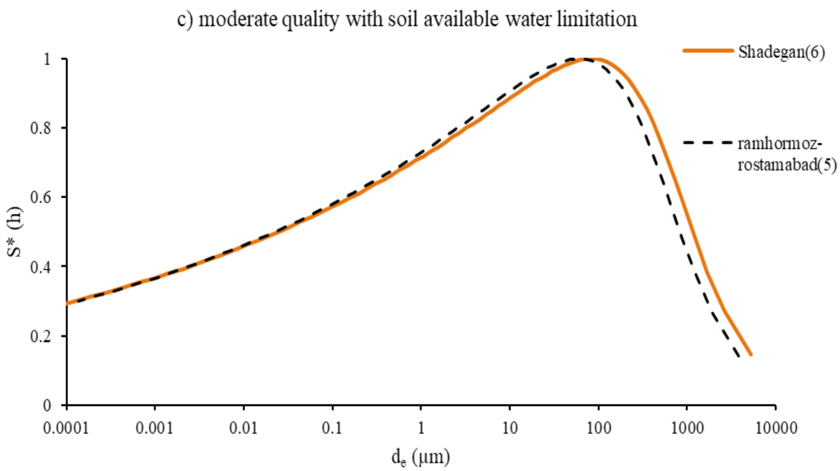


Fig. 1. The pore size distribution curves for the studied calcareous soil series

Table 5. Location and shape parameters for the pore volume distributions of the dominant series of calcareous soils of the Khuzestan province as good (soil series without any limitation), moderate (soil series with only one limitation including aeration or soil available water) or poor soil physical quality (soil series with both aeration and soil available water limitations)

Soil physical quality category	Limitations	Soil	Locations parameters			Shape parameters		
			d_{mean} (μm)	d_{median} (μm)	d_{mode} (μm)	SD	Skewness	Kurtosis
Good	no limitation	Ramhormoz-Rostamabad 1	5.37	14.75	128.18	132.63	-0.396	1.14
Moderate	aeration	Khorramshar 1	0.06	0.23	4.11	404.44	-0.417	1.14
		Ahvaz-Hamedeyeh	0.12	0.36	3.82	178.92	-0.403	1.14
		South Ahvaz	10.17	11.12	13.45	3.16	-0.15	1.14
		Ramhormoz-Bazidi	0.34	1.32	26.57	487.92	-0.42	1.14
		Khorramshar 2	0.30	0.72	4.58	79.46	-0.38	1.15
	Soil water available	Ramhormoz-Rostamabad 2	0.07	0.51	60.34	6569.8	-0.44	1.12
		Shadegan	0.07	0.58	82.26	8552.3	-0.44	1.12
Poor	aeration and soil available water	south-east Ahvaz	1.36	5.14	96.68	440.85	-0.42	1.14

The soil pore volume distribution curve in the good group was used as the optimal pore volume distribution (Fig. 1). The curves of the moderate group with the aeration limitation had a normalized pore-volume distribution, with smaller densities of larger pores than the good group (except in curves of south Ahvaz and Ramhormoz-Bazidi). While, the curves of the moderate group with the soil available water limitation had a pore-volume distribution with more densities of smaller pores than the good group.

The skewness and kurtosis values of the moderate and poor groups were similar to those of the good group (Table 5). This corresponds with the results of Reynolds *et al.* (2009) and Moncada *et al.* (2014), who mentioned that evidently the loss of aeration capacity and structural quality affects the location parameters of the pore volume distributions much more than the shape parameters. The d_{mode}, d_{mean}, d_{median} of the good group were greater than the mean values of the other groups (Table 5). The d_{mode} value (128.18 μm) was consistent with the domain optimal d_{mode} range of 120 to 140 μm proposed by Reynolds *et al.* (2009) and the d_{mode} value of 125.6 μm proposed by Moncada *et al.* (2014) for soils grouped as the ones with good soil physical quality.

Of course, it should be noted that based on the standard deviation index (as a curve shape indicator), there can be described some probability restrictions. In SD = 1, all of the pores are of one size, and with increasing SD, the diversity in the particle size increases (Blott and Pye 2001). High levels of SD in the moderate physical quality group with limited available water indicate a very wide range of pore size in the soil and a high frequency of very fine pores (the soil series in this group have the lowest of skidding parameters in Table 5). The minimum of SD (3.16) was observed in the southern soil of Ahvaz. However, soil series had the highest mean pore size, but d_{mean}, d_{median} and d_{mode} values were found to be very close, which confirms the very low variety of pores in different sizes due to high soil bulk density and compaction. As shown in Fig. 1, the pore distribution curve of this soil series is very different with other soils of moderate quality.

CONCLUSIONS

1. The dominant series of calcareous soils in the Khuzestan province had mostly a medium to fine soil texture, and in 90% of the studied soils, the soil salinity was more than 4 dS m^{-1}.
2. The assessment of soil physical quality based on Dexter's *S* index showed that about 90% of studied soil samples had good or better physical quality ($S > 0.035$).
3. In addition to Dexter's *S* index, some other indicators including plant available water, relative water capacity and macroporosity were also used to evaluate soil physical quality. The results showed that only 11% of studied calcareous soil series had a good soil physical quality in terms of soil water available for plant, soil aeration condition, soil drainage and soil water and air balance for maximization of nitrate microbial production. At the same time, 56% of studied calcareous soil series had only proper soil available water capacity, but they restricted in soil aeration and drainage. However, 22% of studied calcareous soil series had limitation on the soil available water. Therefore, the rest of them (11%) due to limitations in the soil available water, aeration and drainage, had the weakest soil physical quality.
4. The results showed that using just Dexter's *S* index is not enough for assessing soil physical quality in calcareous soils which usually suffer from weak aeration and the inability of soil drainage due to inappropriate management, lake of proper crop rotation and high soil compaction. Therefore, it should be mentioned that in evaluating the soil physical quality for calcareous soil series, soil air and water availability should be considered simultaneously. Moreover, in studied soils, because of high soil compaction, the evaluation of macroporosity that effect the soil drainage rate will be very important in evaluating the soil physical quality.

5. As regards soil aeration and drainage limitations (as most important restriction), it resulted in reduced soil physical quality in dominant calcareous soil series of the Khuzestan province, using such methods as controlled drainage systems, conservation agriculture and crop rotation may be improved the soil physical quality.

REFERENCES

[1] Andrews, S.S., Karlen, D.L., Cambardella, C.A., 2004. *The soil management assessment framework: A quantitative soil quality evaluation method*. Soil Science Society of America Journal, 68: 1945–1962.

[2] Aparicio, V.C., Costa, J.L., 2007. *Soil quality indicators under continuous cropping systems in the Argentinean Pampas*. Soil and Tillage Research, 96: 155–165. DOI: 10.1016/j.still.2007.05.006

[3] Arshad, M.A., Martin, S., 2002. *Identifying critical limits for soil quality indicators in agro-ecosystems*. Agriculture, Ecosystems & Environment, 88: 153–160. DOI: 10.1016/S0167-8809(01)00252-3

[4] Assouline, S., Or, D., 2014. *The concept of field capacity revisited: Defining intrinsic static and dynamic criteria for soil internal drainage dynamics*. Water Resource Research, 50(6): 4787–4802. DOI: 10.1002/2014WR015475

[5] Austin, A.T., Vivanco, L. 2006. *Plant litter decomposition in a semi-arid ecosystem controlled by photodegradation*. Nature, 442: 555–558. DOI: 10.1038/nature05038

[6] Batey, T., 2009. *Soil compaction and soil management – a review*. Soil Use and Management, 25: 335–345. DOI: 10.1111/j.1475-2743.2009.00236.x

[7] Batey, T., McKenzie, D.C., 2006. *Soil compaction: identification directly in the field*. Soil Use and Management, 22(2): 123–131. DOI: 10.1111/j.1475-2743.2006.00017.x

[8] Blott, S.J., Pye, K., 2001. *Gradistat: A grain size distribution and statistics package for the analysis of unconsolidated sediments*. Earth Surface Processes and Landforms, 26: 1237–1248. DOI: 10.1002/esp.261

[9] Cassel, D.K., Nielsen, D.R., 1986. *Field capacity and available water capacity*. In A. Klute (ed.), Methods of Soil Analysis Part 1. Physical and Mineralogical Methods. Agronomy Monograph 9, ASA-SSSA Publishing, Madison, WI, pp. 901–926.

[10] Cockroft, B., Olsson, K.A., 1997. *Case study of soil quality in south-eastern Australia: Management of structure for roots in duplex soils.* In E.G. Gregorich, M.R. Carter (eds.), Soil Quality for Crop Production and Ecosystem Health. Elsevier, New York, pp. 339–350. DOI: 10.1016/S0166-2481(97)80043-8

[11] Dane, J.H., Hopmans, J.W., 2002. *Pressure cell*. In J.H. Dane, G.C. Topp (eds.), Methods of Soil Analysis. Part 4, Physical Methods. SSSA Book Series. Soil Science Society of America, Madison, pp. 684–688.

[12] de Jong van Lier, Q., 2014. *Revisiting the S-index for soil physical quality and its use in Brazil*. Revista Brasileira de Ciencia do Solo, 38: 1–10. DOI: 10.1590/S0100-06832014000100001

[13] Dexter, A.R., 2004a. *Soil physical quality. Part I: Theory, effects of soil texture, density, and organic matter, and effects on root growth*. Geoderma, 120: 201–214. DOI: 10.1016/j.geoderma.2003.09.004

[14] Dexter, A.R., 2004b. *Soil physical quality: Part III. Unsaturated hydraulic conductivity and general conclusions about S-theory.* Geoderma, 120: 227–239. DOI: 10.1016/j.geoderma.2003.09.006

[15] Dexter, A.R., Czyz, E.A., 2007. *Applications of S-theory in the study of soil physical degradation and its consequences*. Land Degradation & Development, 18: 369–381. DOI: 10.1002/ldr.779

[16] Dexter, A.R., Richard, G., 2009. *Tillage of soils in relation to their bi-modal pore size distributions.* Soil and Tillage Research, 103(1): 113–118. DOI: 10.1016/j.still.2008.10.001

[17] Doran, J.W., Mielke, L.N., Power, J.F., 1990. *Microbial activity as regulated by soil water-filled pore space. Symposium III-3, Ecology of Soil Microorganisms in the Microhabitat Environments III.* Transactions of the 14th International Congress of Soil Science. August 12–18, Kyoto, Japan, pp. 94–99.

[18] Drewry, J.J., Cameron, K.C., Buchan, G.D., 2001. *Effect of simulated dairy cow treading on soil physical properties and ryegrass pasture yield*. New Zealand Journal of Agricultural Research, 44: 181–190. DOI: 10.1080/00288233.2001.9513476

[19] Drewry, J.J., Cameron, K.C., Buchan, G.D., 2008. *Pasture yield and soil physical property responses to soil compaction from treading and grazing – a review*. Australian Journal of Soil Research, 46: 237–256. DOI: 10.1071/SR07125

[20] Drewry, J.J., Paton, R.J., 2005. *Soil physical quality under cattle grazing of a winter-fed brassica crop*. Australian Journal of Soil Research, 43: 525–531. DOI: 10.1071/SR04122

[21] Gate, O.P., Czyz, E.A., Dexter, A.R., 2006. *Soil physical quality, S, as a basis for relationships between some key physical properties of arable soils.* Advances in GeoEcology, 38: 102–109. DOI: 10.1016/j.still.2012.01.020

[22] Gee, G.W., Or, D., 2002. *Particle-size analysis*. In J.H. Dane, G.C. Topp (eds.), Methods of Soil Analysis. Part 4. Physical Methods, SSSA Book Series. Soil Science Society of America, Madison, pp. 255–293.

[23] Ghiberto, P.J., Imhoff, S., Libardi, P.L., da Silva, A.P., Tormena, C.A., Pilatti, M.A., 2015. *Soil physical quality by a global index.* Scientia Agricola, 72(2): 167–174. DOI: 10.1590/0103-9016-2013-0414

[24] Groenevelt, P.H., Grant, C.D., Semetsa, S., 2001. *A new procedure to determine soil water availability*. Australian Journal of Soil Research, 39: 577–598. DOI: 10.1071/SR99084

[25] Grossman, R.B., Reinsch, T.G., 2002. *Bulk density and linear extensibility*. In J.H. Dane, G.C. Clake (eds.), Methods of Soil Analysis. Part 4. Physical Methods: SSSA Book Series. Soil Science Society of America, Madison, pp. 201–228.

[26] Guimaraes, R.M.L., Ball, B.C., Tormena, C.A., Balarezo Giarola, N.F., da Silva, A.P., 2013. *Relating visual evaluation of soil structure to other physical properties in soils of contrasting texture and management.* Soil and Tillage Research, 127: 92–99. DOI: 10.1016/j.still.2012.01.020

[27] Jafarnejadi, A.R., Mousavifazl, S.M.H., Javadzadeh, M. 2019. *Evaluation of some soil physical and chemical properties on soil water retention in dominant calcareous soil series in Khuzestan province*. Journal of Agricultural Engineering, 42(3): 33–47. DOI: 10.22055/agen.2019.29168.1489

[28] Kechavarzi, C., Dawson, Q., Leeds-Harrison, P.B., 2010. *Physical properties of low-lying agricultural peat soils in England.* Geoderma, 154: 196–202. DOI: 10.1016/j.geoderma.2009.08.018

[29] Kirkham, M.B., 2005. *Principles of Soil and Plant Water Relations*. Elsevier Academic Press, Amsterdam.

[30] Kishchuk, B.E., 2000. *Calcareous soil, their properties and potential limitation of conifer growth in southeastern British Columbia and western Alberta: a literature review.* Canadian Forest Service Publications. Inf. Rep. NOR-X- 370.

[31] Lal, R., 2015. *Restoring soil quality to mitigate soil degradation*. Sustainability, 7: 5875–5895. DOI: 10.3390/su7055875

[32] Lewandowski, A., Zumwinkle, M., Fish, A., 1999. *Assessing the soil system a review of soil quality literature*. Minnesota Department of Agriculture Energy and Sustainable Agriculture, 1–71.

[33] Logsdon, S. 2019. *Should upper limit of available water be based on field capacity?* Agrosystems, Geosciences & Environment, 2(1): 1–6. DOI: 10.2134/age2019.08.0066

[34] Meskini-Vishkaee, F., Mirkhani, R., 2019. *Effect of field capacity moisture in determination and evaluation of the soil physical quality indices*. Iranian Journal of Soil and Water Research, 50(4): 836–846.

[35] Meskini-Vishkaee, F., Mohammadi, M.H., Neyshabouri, M.R., 2018. *Revisiting the wet and dry ends of soil integral water capacity using soil and plant properties*. Soil Research, 56(4).

[36] Meyer, P.D., Gee, G., 1999. *Flux-based estimation of field capacity*. Journal of Geotechnical and Geoenvironmental Engineering, 125: 595–599. DOI: 10.1061/(ASCE)1090-0241(1999)125:7(595)

[37] Minasny, B., McBratney, A.B., 2003. *Integral energy as a measure of soil–water availability*. Plant and Soil, 249: 253–262. DOI: 10.1023/A:1022825732324

[38] Moncada, M.P., Ball, B.C., Gabriels, D., Lobo, D., Cornelis, W.M., 2014. *Evaluation of soil physical quality index S for some tropical and temperate medium-textured soils*. Soil Science Society of American Journal, 79: 9–19. DOI: 10.2136/sssaj2014.06.0259

[39] Nachabe, M.H., 1998. *Refining the interpretation of field capacity in the literature*. Journal of Irrigation and Drainage Engineering, 124(4): 230–232. DOI: 10.1061/(ASCE)0733-9437(1998)124:4(230)

[40] Reynolds, W.D., Bowman, B.T., Drury, C.F., Tan, C.S., Lu, X., 2002. *Indicators of good soil physical quality: density and storage parameters*. Geoderma, 110: 131–146. DOI: 10.1016/S0016-7061(02)00228-8

[41] Reynolds, W.D., Drury, C.F., Tan, C.S., Fox, C.A., Yang, X.M., 2009. *Use of indicators and pore volume function characteristics to quantify soil physical quality*. Geoderma, 152: 252–263. DOI: 10.1016/j.geoderma.2009.06.009

[42] Reynolds, W.D., Drury, C.F., Yang, X.M., Tan, C.S., 2008. *Optimal soil physical quality inferred through structural regression and parameter interactions*. Geoderma, 146: 466–474. DOI: 10.1016/j.geoderma.2008.06.017

[43] Reynolds, W.D., Drury, C.F., Yang, X.M., Fox, C.A., Tan, C.S., Zhang, T.Q., 2007. *Land management effects on the near-surface physical quality of a clay loam soil*. Soil and Tillage Research, 96: 316–330. DOI: 10.1016/j.still.2007.07.003

[44] Shekofteh, H., Doustaky, M., Masoudi, A., 2018. *Determining features influencing some soil physical quality indicators and their predictions using decision tree and multiple linear regression models*. Journal of Water and Soil, 32(2): 327–342.

[45] Skopp, J., Jawson, M.D., Doran, J.W., 1990. *Steady-state aerobic microbial activity as a function of soil water content*. Soil Science Society of America Journal, 54: 1619–1625. DOI: 10.2136/sssaj1990.03615995005400060018x

[46] Solomon, D., Lehmann, J., Zech, W., 2000. *Land use effects on soil organic matter properties of chromic luvisols in semi-arid northern Tanzania: carbon, lignin and carbohydrates*. Agriculture, Ecosystems and Environment, 78: 203–213.

[47] Topp, G.C., Reynolds, W.D., Cook, F.J., Kirby, J.M., Carter, M.R., 1997. *Physical attributes of soil quality*. In E.G. Gregorich, M.R. Carter (eds.), Soil Quality for Crop Production and Ecosystem Health. Elsevier, New York, pp. 21–58. DOI: 10.1016/S0166-2481(97)80029-3

[48] Tormena, C.A., da Silva, A.P., Imhoff, S.D.C., Dexter, A.R., 2008. *Quantification of the soil physical quality of a tropical oxisol using the S index*. Scientia Agricola (Piracicaba, Brazil), 65(1): 56–60. DOI: 10.1590/S0103-90162008000100008

[49] Twarakavi, N.K.C., Sakai, M., Simunek, J., 2009. *An objective analysis of the dynamic nature of field capacity*. Water Resources Research, 45: W10410. DOI: 10.1029/2009WR007944

[50] van Genuchten, M.T., 1980. *A closed-form equation for predicting the hydraulic conductivity of unsaturated soils*. Soil Science Society of America Journal, 44: 892–897.

[51] Veihmeyer, F.J., Hendrickson, A.H., 1927. *The relation of soil moisture to cultivation and plant growth*. Proceedings of the 1st International Congress of Soil Science, 3: 498–513.

[52] Walkley, A., Black, T.A., 1934. *An examination of Degtjareff method for determining soil organic matter and a proposed modification of the chromic acid titration method*. Soil Science, 37: 29–38.

[53] Wallace, A., Terry, R.E., 1998. *Soil conditioners, soil quality and soil sustainability*. In A. Wallace, R.E. Terry (eds.), Handbook of Soil Conditioners. Marcel Dekker, New York, pp. 1–41.
[54] Warrick, A.W., 2002. *Soil Physics Companion*. CRC Press LLC, Boca Raton.
[55] Wesseling, J., van Wijk, W.R., 1957. *Soil physical conditions in relation to drain depth*. In J.N. Luthin (ed.), Drainage of Agricultural Lands. American Society of Agronomy, Madison.
[56] White, R.E., 2006. *Principles and Practice of Soil Science*. Blackwell Publishing, Oxford.