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Assessment of the soil structure stability focusing on the high-energy moisture characteristic curve in pasture and arable land uses in semi-arid areas, northeastern Iran**

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A b s t r a c t. Investigating the effects of land use on soil structure in order to prevent the ever-increasing risks of soil degradation is important. The objective of this study was to compare the stability of soil structure using different methods in pasture and arable land uses in northeastern Iran. Soil samples were collected from a depth of 0-20 cm at two sites including pasture and arable land uses. Soil structure stability was determined using tensile strength, soil friability and Dexter's number by focusing on the high-energy moisture characteristic curve procedure. The results showed that there were significant differences between the values of modal suction ($p < 0.05$), volume drainable pores, structural index and stability ratio, the aggregate stability index of the high-energy moisture characteristic curve method ($p < 0.01$), and Dexter's number ($p < 0.01$) in pasture and arable land uses. In addition, the difference ($p < 0.01$) between the values of particulate organic matter in both land uses was significant. In arable land use, stability ratio, particulate organic matter and clay were found to be 10.9, 41.7, and 4.9% less than in pasture land use, respectively, and Dexter's number was found to be 63.1% more than in pasture land use. Considering that the value of stability ratio in pasture land use (0.5345) was significantly greater than that in arable land use (0.4761) and the value of Dexter's in arable land use (122.68) was significantly greater than that in pasture land use (75.20), it may be concluded that the stability of the soil structure in pasture land use is greater than that in arable land use. Also, according to the results obtained, it may be asserted that the high-energy moisture characteristic curve method and Dexter's number are suitable methods for the evaluation of the stability of the soil structure in lands with similar characteristics to those of the study area used in this research.

K e y w o r d s: soil structure, soil aggregates, fast wetting, slow wetting, Dexter's number

1. Introduction

Land use plays vital role in many global phenomena, including the preservation of basic natural resources (especially soil), the environment and global climate. The sustainable use of soil, as one of the basic natural resources, depends on the characteristics of the soil (physical, mechanical, chemical and biological), environmental conditions and land use (Erdogan and Tóth, 2014; Gladys and Peace, 2020; Samaei *et al.*, 2022). The applied arable management practices and the type of land use are the most important factors that affect the physical, biological and chemical properties of the soil and, consequently, the quality of the soil (Ghaemi *et al.*, 2014; Derakhshan-Babaei *et al.*, 2021; Gholoubi *et al.*, 2019a; Gholoubi *et al.*, 2018; Riahinia and Emami, 2021). The applied management method and the type of land use cause major changes in soil organic carbon. In fact, the type of land use system is an important factor which determines the content of soil organic matter and its effects have a major influence over the content and quality of input for the formation of plant residues such as leaves

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and fine roots and also on the intensity of leaf decomposition and the sustainable processing of soil organic matter. In arable fields, intensive tillage and the removal of plant biomass from fields causes a reduction in the level of soil organic matter (Li *et al.,* 2007; Romkens *et al.,* 1999).

The stability of the soil structure is considered to be a key indicator used to evaluate soil quality and health for the sustainable use of land resources (Samaei *et al.*, 2022; Chahal and Eerd, 2019; Qi *et al.*, 2009; Emami *et al.*, 2012; Shahab *et al.*, 2018). Soil aggregate stability is very important for improving the physical, biological and chemical properties of the soil (Nweke and Nnabude, 2015; Zaker and Emami, 2019). The soil structure depends to a great extent on the combination of clay particles with organic matter, this determines physical processes such as the self-organization, absorption, disposal and storage of soil water (Dexter *et al.*, 2008; De-Jonge *et al.*, 2009; Resurreccion *et al.*, 2011; Farahani *et al.*, 2019).

According to the intended purpose of the soil structure measurements, it is necessary to choose an appropriate method (Mamedov *et al.*, 2020). For the evaluation and determination of soil structure stability, several methods and aggregate stability indicators such as the fractal dimension (D), the water-stable soil stability rate (WSAR), the geometric mean diameter (GMD) and the mean weighted diameter (MWD) of the aggregates, as well as the application of ultrasonic energy have been proposed (Levy and Mamedov, 2002). Also, Dexter's number, the tensile strength and friability are indicators of soil structure stability (Dexter and Watts, 2000; Dexter, 2004; Dexter *et al.*, 2008). Dexter's number is an effective and useful index for grouping soils based on the clay content associated with organic carbon (complex clay), the water-holding capacity of the soil and its structural stability (Dexter *et al.*, 2008; Naveed *et al.*, 2012).

The tensile strength (*TS*) is the most important aspect of soil microscopic structure and also a dynamic and sensitive property of the soil. *TS* is the force per unit area required to break soil aggregates into smaller particles (Imhoff *et al.*, 2002; Dexter, 2004). Measuring the *TS* of soil aggregates is also used to evaluate the stability of soil structure against mechanical stresses (Munkholm *et al.*, 2002; Dexter *et al.*, 2008). The *TS* value is influenced by soil texture, soil moisture content, wet and dry cycles, porosity, the concentration of cations, dispersible clay, the size and type of clay particles, soil organic matter and the chemistry of the soil solution (Munkholm *et al.*, 2002; Barzegar *et al.*, 1995; Kay and Dexter, 1992). Soil friability (*FS*) is an important physical attribute of soil. *FS* is the tendency of an unconfined soil mass to crumble under applied stresses and break down into smaller pieces that fall within a certain size range (Utomo and Dexter, 1981).

One of the relatively new methods used to determine the stability of the soil structure and aggregate is the high-energy moisture characteristic curve method, however, this method has received less attention and undergone less investigation than the more well established methods. The high-energy moisture characteristic curve (HEMC) method is used to measure moisture characteristic curves at a matric suction range of 0 to 50 hPa under a controlled rate of wetting aggregates (slow wetting as compared to fast wetting). The energy of entrapped air and hydration are the only forces responsible for aggregate slaking. This method is very sensitive for the detection of small changes in the stability of the soil structure caused by land use and soil management (Pierson and Mulla, 1989; Levy and Mamedov, 2002; Poch and Antunez, 2010). In this method, the difference in the soil moisture characteristic curve in the high-energy domain in two modes of slow and fast wetting is considered as an indicator of soil stability (Pierson and Mulla, 1989). Many researchers have shown that the HEMC method is able to detect small changes in soil aggregate and structural stability (Childs, 1942; Collis-George and Figueroa, 1984; Pierson and Mulla, 1989; Norton *et al.*, 2006; De-Campos *et al.*, 2009; Mamedov *et al.*, 2010; 2015; Gholoubi *et al.*, 2019b).

Lado *et al.* (2004) investigated the stability of the soil structure in the case of two different land uses (grass field and corn field) using the HEMC method. Their results showed that the amount of *SI* in the grass field was 4 times greater than it was in the corn field. Ghuolobi *et al.* (2019b) investigated the stability of the soil structure in two types of land use (forest and tea farm) using the HEMC method. They found that the stability index values determined using the HEMC method were higher than those on the tea farm due to the presence of organic carbon and clay content in forest land use. By investigating the effect of land use on soil organic matter and soil physical properties Celik (2005) reported that in pasture land use, soil aggregates larger than 4 mm were dominant, while in agricultural land use, soil aggregates smaller than 0.5 mm were observed. Naveed *et al.* (2012) reported that Dexter's n value in different land uses varied from 1.79 to 195 according to the organic carbon content of the soil. The significant effect of land use on the parameters of soil structure stability as determined using the HEMC method has been reported in the literature (Gholoubi *et al.*, 2019b and Mamedov *et al.*, 2020). For example, Mamedov *et al.* (2020) found that the values of modal suction (*MS*), structural stability index (*SI*) and stability ratio (*SR*) differed significantly according to the different land uses applied.

In introducing a suitable and effective method of soil structure determination, it is important to reflect the small changes in soil structure which occur, especially in arid and semi-arid areas. In addition, the evaluation of soil structure stability for different land uses is necessary in order to prevent soil degradation and to achieve sustainable soil management. Moreover, it was found that soil tensile strength, its friability, and the water-stability of soil aggregates (WSA) represent changes in the structure of the soil (Collisp-George and Figueroa, 1984; Pierson and Mulla, 1989; Ame'zketa, 1999; Gholoubi *et al.*, 2019b; Amjadi *et al.*, 2021; Farahani *et al.*, 2022), but it was not established which method could be used to indicate the differences between soil structure in semi-arid regions that contain low organic matter. In addition, it would seem that Dexter's number may be used to readily evaluate the stability of the soil structure because only two easily available soil characteristics (*i.e.* clay and OM) are required to determine this index. Since the soil structure in arid and semi-arid regions is weak and the differences between the soil structure stability values was found to be low, it was hypothesized that: 1) the HEMC method should be able to distinguish between the small differences between soil structure in this area and 2) Dexter's number could be used as an alternative, both a convenient and suitable method to evaluate the stability of the soil structure. Therefore, the objectives of this research were: 1) to compare the soil structure stability using different methods including Dexter's number, tensile strength, soil friability, and the high-energy moisture characteristic curve (HEMC) for arable and pasture land uses in a semi-arid region; 2) to select a suitable method/indicator for assessing the soil structure in arid and semi-arid regions.

2. Materials and methods

2.1. Description of the study area and soil sampling

The studied area is located at 36˚, 25', 0'' north latitude and 59˚, 25', 0'' east longitude in the northwest of the Khorasan Razavi Province (Mashhad) in northeastern Iran (Fig. 1). The extent of the study area was 22 000 ha. In terms of stratigraphy and lithology, the studied area includes sediments related to the Paleozoic era, which has a Permian-ultrabasic sedimentary metamorphic series. Also, this area has an ophiolite complex and includes ultramafic and mafic rocks (Aghebati *et al.*, 2018). Based on its Soil Taxonomy the soil type of the studied area is Aridisol (Soil Survey Staff, 2022; Tóth *et al.*, 2022).

In this study, two land uses, agriculture (15 years of rainfed wheat cultivation) and pasture (natural and virgin with little grazing), were selected. The selected sampling points had similar conditions (for each pair of sampling points for pasture and agricultural land use) in terms of physiography, topography, geology and climate, so that the stability of the soil structure for both land uses was investigated (Fig. 2). The soil samples were randomly taken using a soil core to obtain a sample for each land use. The crops grown in the arable and pasture land use sections were *Triticum aestivum* and *Alhagi maurorum*, respectively. The climate of this area is cold and semi-arid, with an average of annual precipitation and temperature of ~ 253 mm and 14°C respectively, and the highest rainfall occurs in spring and winter. In total, 120 soil samples from pasture (60 samples) and arable (60 samples) land uses were taken from a soil depth of 0 to 20 cm in January 2021, after ploughing (Moldboard plough) in the case of the agriculture lands and at the same time from the natural pasture. The samples of soil were air-dried and passed through a 2 mm sieve to prepare them for physical and chemical analysis. Aggregates of soil (4-8 mm and 0.5-1 mm) were also collected (after sieving) and stored in closed containers resistant to crushing until the time of testing.

2.2. Laboratory analyses

In order to evaluate the structural stability of the soil, some chemical and physical properties including bulk density (BD), clay, silt and sand contents, electrical conductivity (EC), particulate organic matter (POM) and soil organic carbon (*SOC*) were determined. The contents of sand, silt and clay were measured using a hydrometer

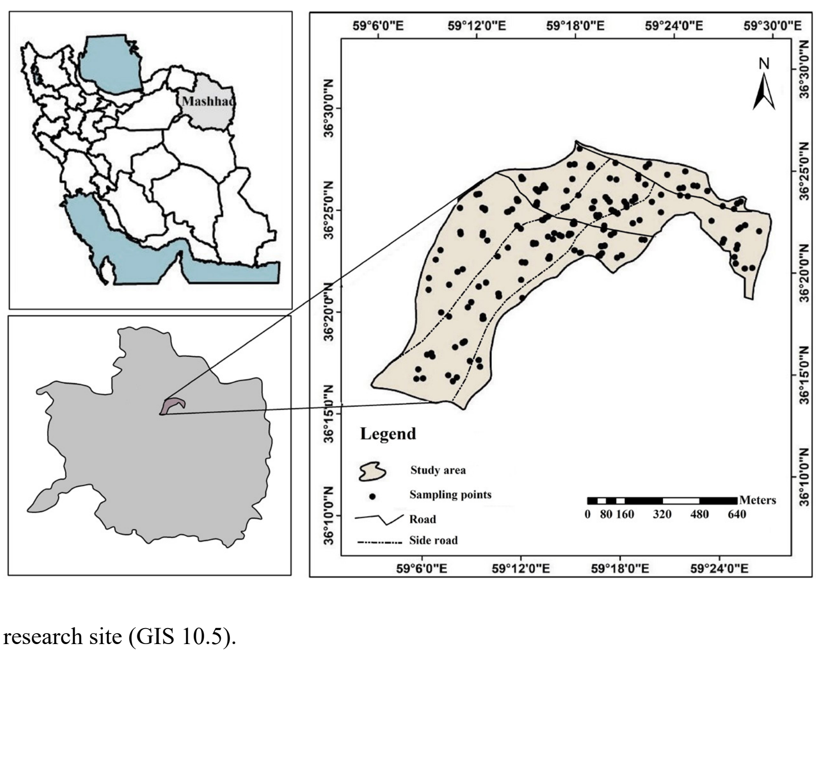

Fig. 1. Location of the research site (GIS 10.5).

Fig. 2. Schematic landscape of studied area (left: pasture, right: arable).

method (Bouyoucos, 1951). The bulk density was measured using undisturbed core samples (Blacke and Hartge, 1986). The organic carbon of the soil was measured using the Walkley-Black method (Nelson and Summers, 1982). The electrical conductivity of the soil was measured in the soil extract using a ratio of soil/deionized water of 1:2.5 w/v (Thomas, 1996). The aggregate stability and soil structure stability were determined using tensile strength (*TS*), soil friability (*FS*), Dexter's number (n) and high-energy moisture characteristic curve (HEMC) methods.

In order to measure the particulate organic matter (POM), a 5% sodium hexametaphosphate solution was added to a predetermined amount of air-dried soil and shaken, then this suspension was poured onto a 53 µm sieve and washed with distilled water until the output water became clear. The remaining material on the sieve, which included sand particles and particulate organic materials, were placed in an oven at a temperature of 50 to 60°C for 24 h (Six *et al.*, 1998). The weight loss on ignition (WLOI) method was used for the quantitative measurement of particulate organic matter. Based on this method, the materials placed in the oven (particulate organic materials and sand particles) were first weighed and then placed in a furnace at a temperature of 450°C, and the remaining materials were then weighed again (Cambardella *et al.*, 2001). Dexter's number (n) was calculated based on the content of the clay fraction and the content of soil organic carbon (*SOC*) using Eq. (1) (Dexter *et al.*, 2008):

$$n = \frac{Cl}{SOC}, \tag{1}$$

where: n is Dexter's number, and Cl and SOC are the percentage of clay and organic carbon in the soil.

In order to determine the tensile strength (*TS*), the force required to crack an individual aggregate (4-8 mm) was measured. For this purpose, 30 aggregates from each soil sample were randomly selected for each test and weighed separately, they were then broken with a loading speed of 1.2 mm min^{-1} in air-dry conditions with a moisture equivalent to a matric suction of 5 000 hPa, the maximum breaking force was measured using an electric uniaxial compression test. For each soil sample, 60 soil aggregates were tested under two moisture conditions. A total of 3 600 (60 soil samples × 30 soil aggregates × 2 moisture contents) aggregate tensile strength tests were performed (Dexter and Kroesbergen, 1985; Braunack *et al.*, 1979) and the results were determined using Eq. (2):

$$TS = \frac{0.576F}{d_{eff}^2}, \tag{2}$$

where: TS (kPa) is the aggregate tensile strength, F (N) is the compressive force required to break down the soil aggregate and d^2_{eff} (mm) is the effective diameter of the soil aggregate. The value of d_{eff} was obtained using Eq. (3):

$$d_{eff} = d_0 \left(\frac{M_a}{M_0}\right)^{1/3}, \tag{3}$$

where: d_0 is the average diameter of the soil aggregates (d_0 = 6 mm), M_a is the weight of the soil aggregates and M_0 is the average weight of 30 soil aggregates.

Equation (4) was used to calculate soil friability (*FS*) (Watts and Dexter, 1998):

$$FS = \frac{\sigma TS}{\overline{TS}} \pm \frac{\sigma TS}{\overline{TS}\sqrt{2n}}, \tag{4}$$

where: FS is the index of soil friability ($0.4 < FS < 0.05$), σTS is the standard deviation of the tensile strength of the aggregates, $\overline{TS}$ is the average tensile strength, and n is the number of soil aggregates (n=30). The second part of the equation represents the standard error of the coefficient of variation.

2.3. Measuring the stability of soil structure using the high-energy moisture characteristic curve (HEMC) method

In this procedure, aggregates with a certain diameter (500-1 000 µm) were collected through sieving them from air-dried soil, 5 g of these aggregates were transferred to PVC cylinders with a height of 20 mm and the same diameter, they were wetted in two ways; at slow and fast speeds. A sand box was used for slow wetting. For fast wetting, the samples were promptly immersed in distilled water and remained there for 24 h (Poch and Antunez, 2010), then the prepared core soil samples were placed in a sand-box and the moisture characteristic curves were plotted for both fast and slow wetted samples at 5 hPa interval suctions from 0 to 50 hPa (Bearden, 2001). After the achievement of a steady state at 50 hPa suction, the aggregates were dried in an oven and their dry weights were measured. In order to determine the values of the parameters of the Van Genuchten model (1980), the soil moisture characteristic curve was fitted using this model by applying Eq. (5) to the data of the high-energy range in Excel (Solver) and the contents of the gravimetric water (θ) were calculated as function of the matric suction (ψ_m) (Levy and Mamedov, 2002):

$$\theta = \theta r + (\theta s - \theta r)\left[\frac{1}{1+(\alpha\psi)^n}\right]^{1-\frac{1}{n}} + A\psi^2 + B\psi + C, \quad (5)$$

where: θ (g g^{-1}) is the water content, θr and θs (g g^{-1}) are the contents of the residual and saturated gravity water, respectively, α (h Pa^{-1}) and n (–) are the steepness of the water retention curve and the empirical parameter, ψ (hPa) is the matric potential while C, A and B are the quadratic terms used to improve the fitting of the model to the water retention curve.

Then, the indices of structure stability including the volume of the drainable pores (VDP), the modal suction (MS), and the structural stability index (SI) were inferred from the curves of the specific water capacity ($d\theta/d\psi$) and the differences between the water retention values were determined by using a modified van Genuchten model (Levy and Mamedov, 2002; Pierson and Mulla, 1989) by applying Eq. (6):

$$d\theta/d\psi = (\theta s - \theta r)\,[1+(\alpha\psi)^n]\,(1/n-1)\,(1/n-1)\,(\alpha\psi)^n\, n/[\psi\,(1+(\alpha\psi)^n)] + 2A\psi + B. \quad (6)$$

The parameters of this equation are the same as those used in Eq. (5) (Pierson and Mulla, 1989).

Then, the structural stability index (SI) was calculated using the Childs' index (Mamedov *et al.*, 2015), by applying Eq. (7):

$$SI = \frac{VDP}{MS}, \quad (7)$$

where: SI (hPa^{-1}) is the structural stability index, VDP (kg kg^{-1}) is the volume of drainable pores and MS (hPa) is the modal suction corresponding to the matric potential at the inflection point of specific water capacity curves (Fig. 3a) which corresponds to the pore-size distribution frequency.

After calculating the stability index for both the slow and fast wetting methods, the stability ratio was determined by applying Eq. (8):

$$SR = \frac{SI_{fast}}{SI_{slow}}, \quad (8)$$

where: SR is the stability ratio, $0 < SR < 1$, the closer it is to one, the more stable the soil, SI_{fast} is the structural stability index for fast wetting, SI_{slow} is the structural stability index for slow wetting.

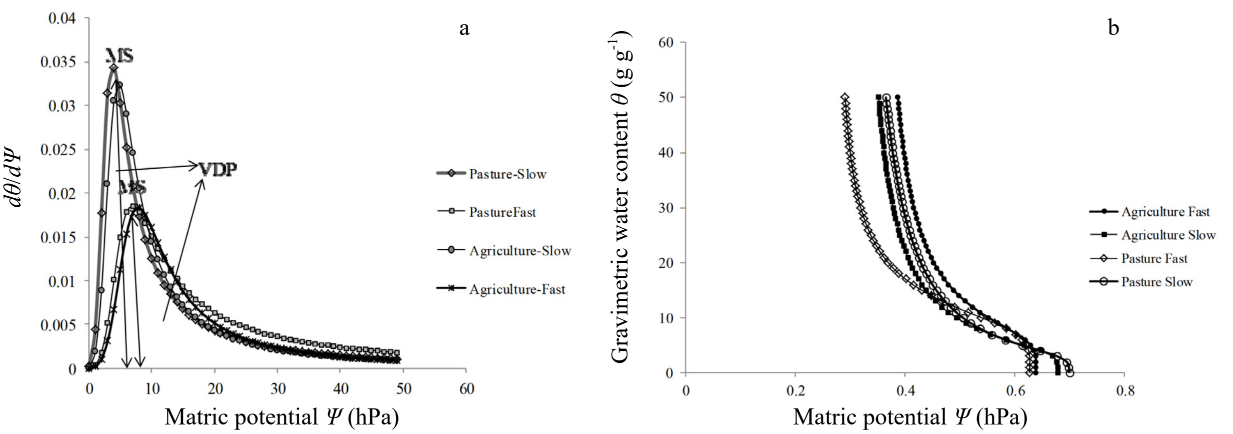

Fig. 3. Specific water capacity curves (a), VDP – volume drainable pores, MS – modal suction and $SWRC$ (b) obtained with the high-energy moisture characteristics (HEMC) method using slow and fast wetted aggregates in pasture and arable land uses.

2.4. Statistical analysis

A statistical analysis of the data was conducted using SPSS 16 and JMP 8 software. In order to analyse and compare the data, a normality test was first carried out (Kolmogorov-Smirnov test). Then, a t-test with a confidence interval of 95% was used in order to compare and investigate the soil structure stability using parameters measured in pasture and arable land uses.

3. Results

3.1. Physical and chemical properties of the soil in arable and pasture uses

In this study, some of the chemical and physical characteristics affecting soil structure stability such as electrical conductivity, bulk density, soil texture, organic carbon and particulate organic matter were determined (Table 1). According to the results of this research, the soil texture in pasture land use was loam, and the soil in arable land use was found to be loam and sandy loam. In addition, the values of soil EC and bulk density in the pasture are significantly ($p < 0.01$) lower than those of the arable soils. Also, in pasture soils, the level of organic carbon ($p < 0.01$) and particulate organic matter were significantly ($p < 0.05$) greater than those found in arable soils.

3.2. Tensile strength (*TS*), soil friability (*FS*) and Dexter's number (n)

The results of a comparison made between the indicators of soil structure stability include tensile strength (TS_{DR} and TS_W), soil friability (FS_{DR} and FS_W) and Dexter's number (n) these values are shown in Table 2 for both land uses of pasture and agricultural. According to the statistical analysis, the friability and tensile strength of aggregates under two moisture conditions in pasture and arable land uses were not significantly different (Table 2). Dexter's number in pasture land use (Table 2), was significantly greater than that produced by arable land use. Also, in both pasture and arable land uses Dexter's number was greater than 10 ($n > 10$).

3.3. The high-energy moisture characteristic curve (HEMC)

The results of the soil structure stability indicators which include volume drainable pores (*VDP*), modal suction (*MS*) and the structural stability index (*SI*) are shown in Table 3. The statistical analysis showed that the values of *MS* and *SI* at two wetting rates (fast and slow) were significantly different ($p < 0.05$ and $p < 0.01$, respectively) in pasture and arable land uses. The value of *VDP* at the two wetting rates examined was also significantly different ($p < 0.01$) in pasture and arable land use. The values of *MS* at the two wetting rates examined were significantly greater in arable land use than in the pasture soils. Also, the values of *MS* for the slow wetting rate in both land uses were lower than those for the fast wetting rate (Table 3, Fig. 3a), while the values of *VDP* for the slow wetting rate in both land uses were greater than those for the fast wetting rate. The value of *SI* at the two wetting rates examined was greater in pasture land use than those produced by arable land use, which may be due to the greater amount of organic matter in pasture land use (Tables 3 and 4). The wetting speed of the aggregates had a significant effect on the shape and slope of HEMC (Fig. 3a, b). According to the statistical analysis (Table 3), the values of SR were significantly different ($p < 0.01$) in pasture and arable land uses. Also, the values of *SR* were greater than zero and lower than one ($0 < SR < 1$) in both land uses.

Correlation coefficients between soil organic carbon (*SOC*) and indicators of structure stability

There was a significant correlation ($p < 0.01$) between soil organic carbon (*SOC*) and various indices of structure stability (*SI*, *SR* and Dexter's number). Significant correlation coefficients were found between soil organic carbon

Table 1. Physicochemical characteristics (mean and standard error) of the soil sampled from 0-20 cm

Land use	Texture	BD (g cm^{-3})	Clay (g kg^{-1})	Silt (g kg^{-1})	Sand (g kg^{-1})	EC (dSm^{-1})	*SOC* (g kg^{-1})	POM (g kg^{-1})
Pasture	L	1.39**	197.0*	347.1**	455.9**	0.15**	2.67**	2.42*
Arable	L, SL	1.52**	187.3*	319.5**	493.1**	0.17**	1.82**	1.41*
Std. error	–	0.01	0.30	0.39	0.59	0.01	0.04	0.03
				Pasture				
Max	–	1.48	228.6	395.2	500.4	0.16	3.90	2.90
Min	–	1.31	175.0	303.2	376.2	0.13	1.76	1.80
Std. error	–	0.01	0.29	0.46	0.61	0.01	0.05	0.03
				Arable				
Max	–	1.65	215.8	387.7	577.3	0.19	2.53	2.10
Min	–	1.44	155.5	254.8	416.9	0.14	0.98	0.60
Std. error	–	0.01	0.30	0.47	0.62	0.01	0.04	0.03

Significant at: *p-value < 0.05, **p-value < 0.01. L – loam, SL – sandy loam, BD – bulk density, Clay – clay content, EC – electrical conductivity, *SOC* – soil organic carbon, POM – particulate organic matter, Max – maximum, Min – minimum.

Table 2. Mean comparisons of tensile strength, friability and Dexter's number in pasture and arable land uses

Land use	TS_{DR} (kPa)	TS_W (kPa)	FS_{DR}	FS_W	Dexter's n
Pasture	0.050[a]	0.038[a]	0.520[a]	0.690[a]	75.200[a]
Arable	0.039[a]	0.027[a]	0.500[a]	0.670[a]	122.680[b]
Std. error	0.005	0.004	0.035	0.059	5.618
			Pasture		
Max	0.095	0.088	0.890	1.520	107.250
Min	0.012	0.013	0.320	0.400	46.890
Std. error	0.006	0.005	0.040	0.075	2.779
			Arable		
Max	0.054	0.048	0.758	0.889	263.220
Min	0.021	0.012	0.333	0.421	77.170
Std. error	0.002	0.003	0.028	0.036	7.443

TS_{DR} – tensile strength at air dry moisture, TS_W – tensile strength at moisture equivalent to matric suction of 500 hPa, FS_{DR} – soil friability at air dry moisture, FS_W – soil friability at moisture equivalent to matric suction of 500 hPa. Different letters in each column represent the significant differences between pasture and arable land uses.

Table 3. Mean comparison of HEMC indices

Land use	*MS* (hPa)		*VDP* (kg kg^{-1})		*SI* (hPa^{-1})		*SR* (–)
	Fast	Slow	Fast	Slow	Fast	Slow	
Pasture	5.710[b]	3.360[b]	0.3054[a]	0.3358[a]	0.0534[a]	0.0999[a]	0.5345[a]
Arable	7.040[a]	4.240[a]	0.2521[b]	0.3191[b]	0.0358[b]	0.0752[b]	0.4761[b]
Std. error	0.005	0.009	0.0011	0.0008	0.0001	0.0002	0.0012
				Pasture			
Max	5.800	3.410	0.324	0.346	0.056	0.102	0.549
Min	5.540	3.290	0.281	0.325	0.050	0.098	0.510
Std. error	0.006	0.003	0.001	0.0008	0.0001	0.0002	0.001
				Arable			
Max	7.110	4.320	0.266	0.336	0.037	0.077	0.481
Min	6.980	4.130	0.243	0.309	0.034	0.074	0.459
Std. error	0.006	0.003	0.001	0.0008	0.0001	0.0002	0.001

MS – modal suction, *VDP* – volume drainable pores, *SI* – structural stability index, *SR* – stability ratio. Other explanations as in Table 2.

Table 4. Correlation matrix among indices of structural stability (n = 180)

Variables	TS_{DR}	TS_W	FS_{DR}	FS_W	SI_{fast}	SI_{slow}	*SR*	Dexter's n	*SOC*	*Cl*	BD	EC
TS_W	0.122											
FS_{DR}	-0.312**	-0.256**										
FS_W	-0.325**	-0.187*	0.863**									
SI_{fast}	0.320**	0.346**	-0.055	0.035								
SI_{slow}	0.321**	0.339**	-0.047	0.037	0.994**							
SR	0.280**	0.343**	-0.069	0.036	0.979**	0.965**						
Dexter's n	-0.102	-0.194**	-0.067	-0.146	-0.606**	-0.599**	-0.606**					
SOC	0.236**	0.242**	-0.008	0.011	0.708**	0.702**	0.714**	-0.505**				
Cl	0.156*	-0.017	-0.121	0.003	0.284**	0.282**	0.275**	-0.136	0.217**			
BD	-0.278**	-0.333**	0.065	-0.006	-0.786**	-0.789**	-0.750**	0.618**	-0.574**	-0.254**		
EC	-0.112	-0.303**	0.097	0.018	-0.564**	-0.568**	-0.548**	0.251**	-0.354**	0.025	0.371**	
POM	0.255**	0.318**	-0.009	0.054	0.878**	0.864**	0.859**	-0.587**	0.649**	0.172*	-0.728**	-0.496**

**Significant at the p-value < 0.01 probability level, TS_{DR} – tensile strength in air dry moisture, TS_W – tensile strength in moisture equivalent to matric suction of 500 hPa, FS_W – soil friability in moisture equivalent to matric suction of 500 hPa, FS_{DR} – soil friability in air dry moisture, *SOC* – soil organic carbon, SI_{fast} – structural index at fast wetting, SI_{slow} – structural index at slow wetting, *SR* – stability ratio, Dexter's n – Dexter's number, BD – bulk density, *Cl* – clay content, EC – electrical conductivity, POM – particulate organic matter.

and HEMC indices, *TS* and Dexter's number (Table 4). Also, there was a positive correlation found between *SOC* and *TS* in two moisture conditions and also there was a negative and significant correlation found between soil organic carbon and Dexter's number (Table 4).

4. Discussion

The soil organic carbon, clay content, bulk density and EC in both land uses differed significantly. The average clay content in arable soils (18.7%) was slightly less than those of the pasture soils (19.7%). The soil texture in pasture land use was loam, while it was loam and sandy loam in arable land use. The change in soil texture and the lower clay content in arable land use may be related to arable operations, these cause the transfer of fine particles (especially clay) to the subsurface layers and they also cause the coarse fragments to remain in the surface layers (Shamsi *et al.*, 2011). Compared to the results produced by other research efforts (Cambardella and Elliott, 1993; Gholobi *et al.*, 2019b; Mamedov *et al.*, 2020), the lower content of *SOC* and POM (Table 1) in arable land use as compared to pasture land use indicates changes in the soil characteristics in the areas studied. On the other hand, due to the low content of organic matter (*SOC* and POM) in arid and semi-arid regions, it is difficult to determine the appropriate indicators to reveal the differences between different land uses in these regions. Mamedov *et al.* (2021) measured the value of soil organic carbon, clay, EC and pH in crops, bush, grass and forest land uses, using different types of soil including Acrisol, Luvisol and Vertisol, and reported the value of the organic carbon content of the soil in forest land use, these values in Acrisol and Luvisol were found to be greater than those for other land uses. Also, it was found that the values of clay and pH in different land uses of Vertisol were higher than those of other soils, and the values of EC in Acrisol land use were lower than those of other soils.

The greater bulk density in arable land use as compared to pasture land use may be related to the traffic of heavy arable machinery and tools, which compacts the soil, and increases the soil bulk density. The bulk density of the soil is influenced by land use, land management, the content of soil organic matter and particle size distribution and it's also related to soil structure.

In pasture soils, as a result of plant residues and a lack of cultivation, OM and POM increase. On the other hand, as a result of tillage, the level of aeration of arable soils is greater than that of pastures, which accelerates the oxidation of organic carbon and increases the content of output carbon (carbon dioxide) and it also reduces the organic carbon of the soil. When the level of soil organic carbon decreases, POM also decreases, because about 39% of soil OM belongs to the carbon contained in particulate organic materials (Soinne *et al.*, 2016).

In arable land use, agricultural machinery causes the compaction and destruction of the soil structure. By disturbing the soil conventional tillage causes greater and more rapid decomposition of plant residues and ultimately reduces the level of organic matter in the soil. Due to the absence of tillage practices in pasture land use as compared to arable land use (conventional tillage), the content of organic matter, and the water infiltration rate, crop biomass increases and there is a reduction in soil erosion in arid and semi-arid areas (Fuentes *et al.*, 2004). The rate of entry of plant biomass such as leaves and fine roots into the soil is different under various land uses. The value of carbon in the soil is a function of the input of plant residues and their loss from the soil. In pasture soil, due to a lack of cultivation and a higher content of plant residues, there is a balance between the breakdown of soil organic matter and the accumulation of plant residues, but in arable lands, due to the harvest of plant biomass and the lack of a return of plant residues to the soil, this balance does not exist. Also, in arable lands, tillage operations cause the mixing of the lower layers of the soil with a lower percentage of organic carbon with the surface soil containing more organic carbon, and as a result, they cause a decrease in soil organic carbon (Tejada and Gonzalez, 2008; Wang *et al.*, 2014). Organic matter increases the resistance of aggregates against wetting and the structure stability of the soil through two mechanisms, by increasing hydrophobicity and increasing adhesion between particles. On the other hand, organic matter (*SOC*, POM) plays the role of a cement between the soil particles, it stabilizes the aggregates and the soil structure and thereby the formation of macropores increases.

Due to the fact that the value of the friability of the aggregates under two moisture conditions in pasture and arable land uses was more than 0.4 ($FS > 0.4$), the soil from both land uses is considered to be mechanically weak and unstable. As mentioned above, in general terms, the values of both the tensile strength and friability in both land uses were not significant, because in arid and semi-arid areas, soil organic matter content is low and, as a consequence, the soil structure is mechanically weak and unstable. Therefore, it may be concluded that these indices are not suitable for the assessment of soil structure in arid and semi-arid regions.

The value of Dexter's number was found to be greater than 10 in both studied land uses (Table 2), which means that in the case of both land uses, non-complex clay particles were available to connect with free soil organic carbon, because the threshold value of Dexter's number is 10. The value of Dexter's number in arable land use was found to be greater than in pasture land use (~ 2 times). This reflects the fact that the content of non-complex clay particles in this land use is greater than that in pasture land use, which may be due to lower levels of organic carbon in arable land use. Since *SOC* is substantially influenced by land use and management, Dexter's number increases in land which has low organic matter contents. Since the *SOC* value is substantially influenced by land use and management, and therefore Dexter's number increases in land which has low organic matter contents. The range of Dexter's number in pasture land use was about 47-107, while it was 77-263 in arable land use, this shows the substantial effect of land use on Dexter's number (Table 2). It may be concluded that Dexter's number index is one of the important indicators which reflects any changes in the physical behaviour of soil. One of our hypotheses was that the use of Dexter's number may be a suitable method for the evaluation of the stability of the soil structure, and considering that the contents of organic carbon and soil clay are two important characteristics that affect the stability of the soil structure, and are substantially influenced by land use and land management, so the use of Dexter's number could be a suitable and accurate method in the evaluation of the stability of the soil structure in different land uses, especially in arid and semi-arid areas. Even though our results support this hypothesis, further research is recommended.

The values of *MS* at the two wetting rates in arable land use were found to be greater than those of pasture, which may be due to the greater content of organic carbon, clay and the structural porosity in pasture land use. The values of *VDP* at the two wetting rates in pasture land use were greater than those of agricultural land use. The fast wetting of aggregates causes the slaking of aggregates and the formation of more particles with smaller sizes than the original soil aggregates, this in turn changes the pore-size distribution between the particles so that the number of smaller pores increases, thereby increasing *MS* and reducing *VDP*. The destruction of aggregates and their transformation into fine aggregates in arable land use due to agricultural operations reduces the structural index. Also, soil organic carbon is one of the key factors in the creation of aggregates. This improves the structure stability of the soil. As a result, there are more stable aggregates in pasture land use and the structural stability index is increased. The differences between the slow and fast wetting curves were generally attributed to the destruction and slake of aggregates in the fast wetting rate which is due to entrapped air, the hydration of exchangeable cations and the clay surfaces of the soil particles (Norton *et al.*, 2006; Mamedov *et al.*, 2010; Gholoubi *et al.*, 2019b). The value of *SI* at the two wetting rates in pasture land use was greater than that due to arable land use, which could be due to a greater *VDP* value and more organic matter in pasture land use (Tables 3 and 4). *SR* is the most important and main indicator of the HEMC method. *VDP* and *MS* are two sensitive parameters of the HEMC method, which reflects changes in the physical characteristics of the soil, especially in soil structure, and any change (minor and general) in physical characteristics cause changes in these two parameters. *VDP* and *MS* are both influenced by soil pore-size distribution (PSD) and soil structure stability, which are in turn substantially influenced by soil organic matter (*SOC*, POM) content and consequently by land use and management practices. Therefore, it may be concluded that in arid and semi-arid regions, due to the lack of organic matter, the stability of the soil structure is weak, and any change (even minor ones) in *SOC*/POM as a result of land use changes the stability of the soil structure, and the HEMC indices. The value of *SR* in both land uses was greater than zero, and the value of *SR* in pasture land use was approximately 12.3% greater than that in arable land use, which means that the stability of soil aggregates in this land use was greater than that in arable land use, and as a result, the stability of soil structure in pasture land use was greater than that in arable land use, which may be a reason for the higher content of organic matter and clay in this land use.

The results of this research showed that the high-energy moisture curve (HEMC) as a suitable and sensitive method can be used to characterize the stability of the soil structure in arid and semi-arid areas, and it may be asserted that this method is more sensitive to minor changes in soil structure, therefore it can be used to evaluate the stability of soil structure as compared to other methods such as tensile strength and soil friability. The results of this study have confirmed that this method (HEMC method) can be used in arid and semi-arid regions and they can also be used to determine the effect of land use on the soil structure stability (*MS*, *VDP*, *SI*, *SR*) in this area. The lower value of *SI* in our study (in arid and semi-arid areas) as compared to the humid area (Gholoubi *et al.*, 2019b; Mamedov *et al.*, 2020) reflects the important effect of soil organic carbon on the stability of the soil structure, because the content of organic carbon (Table 1) in our studied sites was lower than those determined by the researchers cited above.

The significant positive correlation between *SOC* and the soil structure stability parameters (*SI*, *SR*) was confirmed by the results of Gholoubi *et al*. (2019b) using the HEMC method. They reported a significant positive correlation between *SOC* and *SI* (0.461) and *SR* (0.342). The positive correlation between *SOC* and the HEMC stability indices (SI_{fast} r = 0.708, SI_{slow} r = 0.702 and *SR* r = 0.714) indicates the vital influence of OC on aggregate stability and soil structure stability (Table 4). Organic matter increases the stability of the aggregates and soil structure by increasing the cohesive force between the soil aggregates. Soil structure stability indicators are a function of soil texture, *SOC* content and land use. In this study, the clay content in pasture land use was slightly greater than that in arable lands, however, the content of organic carbon in pasture land use (2.67 g kg^{-1}) was greater than that in arable land use (1.82 g kg^{-1}). Therefore, it may be concluded that the type of land use plays a principal role in the structure sustainability of the soil through the effect exerted by organic carbon. Therefore in soils containing high OM contents, the stability of the soil structure indices such as HEMC increase. The negative and significant correlation between soil organic carbon and Dexter's number indicates a lower Dexter's number, and an increase in organic carbon and aggregate stability.

5. Conclusions

Land use and management have the potential to influence the organic carbon content and particulate organic matter, especially in the surface layer of the soil (0-20 cm), and, as a consequence, influence the stability of aggregates and soil structure. Due to the low level of organic matter and the consequent soil structure stability in arid and semi-arid areas, selecting the most suitable index of soil structure is a challenge. According to the results of the high-energy moisture characteristic curve method structural stability index, stability ratio, modal suction, volume drainable pores the difference between the soil structure stability in both arable and pasture land uses was significant. The values of volume drainable pores and structural stability index at two wetting rates (fast and slow) and also stability ratio in pasture land use were significantly ($p < 0.01$) greater than in arable land use. The gradual (slow) wetting of the soil aggregates provide a better possibility for the release of entrapped air between the aggregates, and as a result, the destruction of the soil structure and clay dispersion is minimized and the stability of the aggregates increases, however, fast wetting decreases the resistance of the aggregates against collapse and the destruction of the aggregates. The high-energy moisture characteristic curve method is sensitive to minor changes in soil structure and therefore can be used to evaluate the stability of soil structure, especially in arid and semi-arid areas with low organic carbon. High and significant correlation coefficients between organic carbon and other physical characteristics of the soil, such as stabili-ty ratio (0.714), indicate the fundamental effect of organic matter on the stability of soil structure. The greater content of soil organic carbon in pasture land use (46.7%) as compared to arable land use revealed the important role of land use in soil organic matter, and structure stability, especially in semi-arid areas. With regard to the importance of organic matter, it should be avoided where there is land use change in a semi-arid region in order to achieve soil sustainability. In addition, it seems that Dexter's number may be used to evaluate the stability of the soil structure, and only two easily available soil characteristics (*i.e.* clay and OM) are required in order to determine this index. Therefore, when we have little information about soil structure, it may be used to assess the results of land use change.

Conflicts of interest: The authors declare no conflict of interest.

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