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Effects of land use and reducing conditions of paddy fields on soil quality and high energy moisture characteristic structural stability indices in North of Iran

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Abstract

The present paper is aimed at investigating the effects of land use (particularly reducing conditions of paddy fields) on soil structural stability as characterized by the high energy moisture characteristic (HEMC) method and finding the relationship between soil structural stability and available water (AW) in Amol city in Mazandaran province, Iran. Land use conversion led to a change in the soil organic matter (OM) content. The highest OM was found in the forest and pasture land uses, being significantly different from those of citrus garden and paddy field land uses. The high values of bulk density in the citrus garden and paddy fields can be attributed to intensive machinery traffic and puddling, respectively. However, bulk density was low in pasture and forest land uses because of high OM and macropores. Forest and the paddy fields had higher soil structural stability due to high OM/Clay ratio. The HEMC indices including volume of drainable pores ratio (VDPR) and stability ratio (SR) were calculated using the modified van Genuchten model, and the ratio of slopes at the inflection point of HEMCs of fast-wetted to slow-wetted soil samples (S_iR) was determined using the van Genuchten model. The HEMC indices showed positive and significant correlations with OM and OM/Clay ratio. By increasing the OM/Clay ratio, greater clay became complexed with organic matter, and thus soil structure stability increased. A strong correlation was observed between VDPR and OM/Clay in citrus garden and paddy fields. Furthermore, there was a significant correlation between VDPR and AW. The highest field capacity and AW were observed in the forest and paddy fields due to high OM and the presence of smectitic clays under reducing conditions, respectively.

Abbreviations

A	Empirical coefficient in the modified van Genuchten model, hPa^{-2}
B	Empirical coefficient in the modified van Genuchten model, hPa^{-1}
C	Empirical coefficient in the modified van Genuchten model, g g^{-1}
CCE	Calcium carbonate equivalent, kg 100 kg^{-1}
$C(\theta)$	Specific water capacity function $= |d\theta/dh|$, hPa^{-1}
EC	Electrical conductivity of saturated soil paste, dS m^{-1}
HEMC	High energy moisture characteristic
h	Matric suction, hPa
h_{modal}	Modal matric suction (matric suction at the peak of specific water capacity function), hPa
$h_{modal-FW}$	Fast wetting h_{modal}, hPa
$h_{modal-SW}$	Slow wetting h_{modal}, hPa
$h_{modal}R$	Ratio of $h_{modal-FW}$ to $h_{modal-SW}$
n	Shape parameter in van Genuchten model
OC	Organic carbon content, kg 100 kg^{-1}

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OM	Organic matter content, kg 100 kg^{-1}
AW	Available water, cm^3 cm^{-3}
pH	pH of saturated soil paste
PTFs	Pedotransfer functions
SI	Structural index, hPa^{-1}
SI$_{FW}$	Fast wetting SI, hPa^{-1}
SI$_{SW}$	Slow wetting SI, hPa^{-1}
S_i	Slope at the inflection point of HEMC, hPa^{-1}
S_iR	Ratio of fast wetting to slow wetting S_i values
SR	Stability ratio
TN	Total nitrogen content, kg 100 kg^{-1}
VDP	Volume of drainable pores, g g^{-1}
VDP$_{FW}$	Fast wetting VDP, g g^{-1}
VDP$_{SW}$	Slow wetting VDP, g g^{-1}
VDPR	Volume of drainable pores ratio
A	Scaling parameter in van Genuchten model, hPa^{-1}
ρ_b	Bulk density, g cm^{-3}
$\theta_{330} = \theta_{FC}$	Soil water content at field capacity, g g^{-1} or cm^3 cm^{-3}
$\theta_{15000} = \theta_{PWP}$	Soil water content at permanent wilting point, g g^{-1} or cm^3 cm^{-3}

Introduction

Soil structure is defined as the spatial arrangement of soil constituents, aggregates and pores and is considered as a dynamic component in the new land management models. Soil structure has significant effect on different processes and phenomena such as root growth and its functions, soil organisms, solute transport, water infiltration, gas exchange and heat transfer. Soil structural stability is the resistance of aggregates when exposed to external forces such as cultivation, harvesting, compaction, irrigation, and erosion (Mamedov and Levy 2013). Aggregate stability is affected by inherent soil properties including organic matter, texture, porosity and temperature, as well as land use, tillage, melting–freezing cycles, organic matter decomposition, microbial activities and plant roots. Soil structure and aggregate stability have direct relationships with soil physical quality (Dexter 2004).

Different methods and indices have been introduced to determine the soil structural stability including wet-sieving method, water-dispersible clay and high energy moisture characteristic (HEMC) method (Mamedov and Levy 2013; Hosseini et al. 2015). The HEMC has been considered as an interesting method for determining aggregate stability of soils in arid and semi-arid regions with a wide range of structural stability (Mamedov et al. 2010, 2014; Mamedov and Levy 2013; Hosseini et al. 2015). The HEMC structural

stability indices are linked with several soil physical processes such as erosion, infiltration rate and runoff (Mamedov and Levy 2013).

Among the factors affecting soil structural stability, organic matter is of particular importance. By creating cationic bonding with clays, neutralizing charges on the surface of clays, and creating hydrophobic coatings on aggregate surfaces, organic compounds protect aggregates against hydric and mechanical forces (Piccolo and Gerzabek 1999). Dexter et al. (2011) found that the presence of organic compounds in the soil decreased readily dispersible clay at matric potentials close to the field capacity. Pierson and Mulla (1990) employed the HEMC method to determine aggregate stability in a sloping erodible area under wheat cultivation in Washington, USA. They found that HEMC indices had significant correlations with soil amorphous iron, available water and clay contents. Frederick and Pierson (1989) used the HEMC method to compare the aggregate stability in long-term land uses with different management practices including an organic farming and a conventionally tilled farm with application of chemical fertilizers. The results showed that the soil water content and organic matter content were significantly higher in the organic farming plots and the structural indices for the fast-wetted aggregates were significantly different among the organic and conventional farms. Although Reganold et al. (1987) did not succeed to differentiate the aggregate stability between the two farming systems using water-to-air permeability ratio, Frederick and Pierson (1989) could find a significant difference using the HEMC method. Mamedov (2014) examined the effects of soil texture and water quality on water retention and structure stability of loam and clay soils using the HEMC method. He found that with an increase in the clay content and electrolyte concentration, and a decrease in the wetting rate, the HEMC indices and parameters including volume of drainable pores (VDP), structural index (SI) and α increased, and the modal suction (i.e., matric suction at the peak of the specific water capacity curve corresponding to most frequent pores, h_{modal}) and n decreased.

Biotic factors may affect soil aggregate stability as well. Hosseini et al. (2015) studied the effect of endophyte symbiosis with tall fescue on structural stability of rhizosphere soil as quantified by HEMC in a range of soils. The results indicated that the presence of plant roots in the rhizosphere increased the VDP and highly decreased the h_{modal} due to formation of stable macropores and reduction of micropores. Presence of roots and mucilage exudation increased the soil organic carbon (OC) content and stability of aggregates against the destructive effects of wetting. Hosseini et al. (2017) investigated the effects of endophyte-infected and non-infected tall fescue residues (0, 1, and 2%) on aggregate stability using the HEMC method in four texturally different soils. The highest values of HEMC aggregate stability

indices were reported for fine-textured soils, indicating that aggregate breakdown was minimized due to stabilization of soil pores by the clay particles and the higher organic matter content. The application of endophyte-infected residues, while increasing OC, increased aggregate stability indicators by up to 50% compared to the control.

Reduction–oxidation processes are frequently happened in the nature and may affect soil structure. There are few published papers about the effect of reduction–oxidation processes on aggregate stability. De-Campos et al. (2007) stimulated the reducing conditions in the laboratory and used the HEMC method to evaluate the aggregate stability in six upland soils (three cultivated soils and three uncultivated soils with different organic carbon contents) in western USA. The reducing conditions were altered using a reactor at controlled temperature and light. They applied five incubation-time treatments for each soil (from one hour to one, three, seven, and fourteen days) with a soil-to-water ratio of 1.01.5. Then, they analyzed the soil organic carbon content and concentrations of other elements in the soil solution collected from each treatment. They found strong and positive correlations between the reduction–oxidation potential (Eh) and HEMC indices. The reducing conditions affected the concentrations of metal elements (Fe and Mn), alkali elements (Mg, Ca and K), and organic carbon content, and as a consequence aggregate stability decreased. The cultivated soils were more sensitive to reducing conditions than uncultivated soils presumably because the uncultivated soil had greater initial organic matter content and aggregate stability. Therefore, short-term reducing conditions could affect soil structure and quality of soil solution. Land use types can affect soil physical and chemical properties and structural stability. In particular, reducing conditions in paddy fields can result in an increase in cation exchange capacity, an increase in soluble Fe due to dissolution of Fe oxides, and an increase in soluble Ca and Mg concentrations. However, reducing condition can decrease the above-mentioned elements in exchangeable sites, soluble K concentration, and clay flocculation, and as a consequence results in greater repulsive forces between negative charges, clay dispersion and aggregate instability. Reducing conditions can result in clay dispersion and a decrease in soil structural stability due to physicochemical changes and an increment in pH (De-Campos et al. 2007). Recently, Saedi et al. (2021) studied the effect of endophyte-tall fescue symbiosis on the root zone quality indicators under different aeration conditions in a greenhouse pot experiment. The results showed that soil structure degradation was intensified under oxygen-limited conditions. However, endophyte symbiosis increased the aggregate stability through the water-repellent exudates and enhanced organic carbon storage especially under oxygen-limited conditions.

The impact of land use on soil quality might be evaluated by monitoring changes in organic matter content, pore size distribution and/or water retention [i.e., water contents at specific matric potentials such as field capacity (θ_{FC}) and permanent wilting point (θ_{PWP})]. Organic matter (OM) can increase soil water retention due to its high surface area and positive influence on soil structure. An increment in the OM and aggregate stability would result in higher pore space in the range of pore sizes corresponding to plant available water (Huntington 2007). The decrease in θ_{FC} and θ_{PWP} as a result of the conversion of forest into agricultural land could be related to the oxidation of organic carbon due to excessive soil tillage. Greater θ_{FC} and θ_{PWP} values in the paddy fields could be due to greater expandable 2:1 newly formed clays (smectites). Fares (2009) concluded that in citrus gardens, the negative effects of water shortage on flowering and fruit set were minimized by maintaining water content above 25%–33% depletion of soil available water from February to May. However, during the remaining part of the growing season, soil available water can be allowed to deplete by 50%–67% before replenishment of the soil water back to θ_{FC}.

To the best of authors' knowledge, no studies have been conducted on the impacts of pasture, forest, and citrus land uses, particularly paddy fields, on soil structural stability as assessed by the HEMC method and its link with available water content. Therefore, the objectives of the present study were to investigate the effect of land uses (particularly paddy fields) on HEMC stability indices and to determine the relations between soil structural stability and available water. Moreover, pedotransfer functions for predicting HEMC stability indices and soil available water were developed using multiple regression. These data and information would be useful for management of the land resources in the region.

Materials and methods

Study site description

This research was carried out in paddy fields of Mazandaran plain to upland forests of Amol, Mazandaran province, Northern Iran. Amol has altitudes of −6–600 m a.s.l (above sea level) and was located at 52° 15′ 37′′ to 52° 19′ 11′′ E longitude and 36° 18′ 46′′ to 36° 33′ 44′′ N latitude, 70 km west of Sari (capital of Mazandaran province), 18 km from the Caspian Sea, 1,00 km northeast of Tehran (Fig. 1). Generally, the region has warm and humid summers and relatively cold winters. Its average annual precipitation and mean annual temperature are 750 mm and 17.4 °C, respectively. The maximum and minimum means of monthly precipitation are 150 and 14 mm that usually occur in July and December, respectively. The climate is classified by
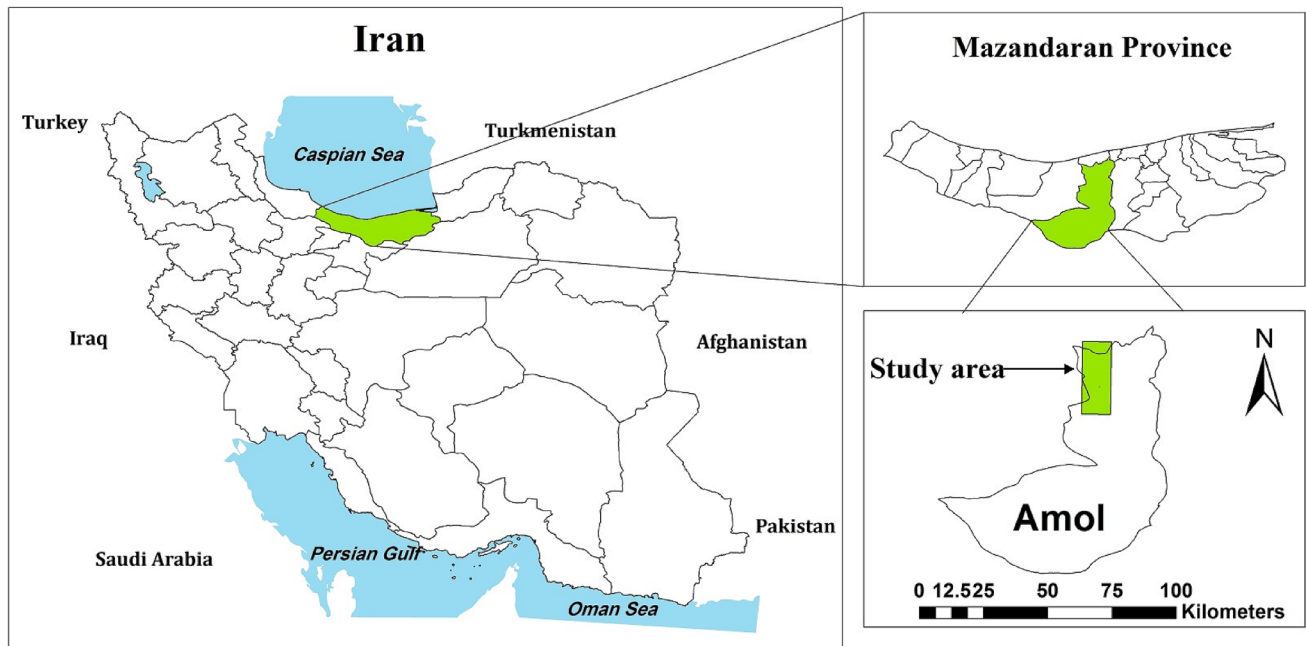
Fig. 1 The location of study area in Amol, Mazandaran province, Iran

the Hansen classification as warm temperate and is highly temperature.

Selection of points for field measurements and soil sampling

A nested network was used for the selection of sampling locations in the region. The points were defined at a regular distance to cover the major land uses in the region: paddy fields, pasture, citrus gardens, and forest (Fig. 2). The coordinates of the points ranged from 52° 21′ 33″ E longitude and 36° 23′ 43″ N latitude to 52° 19′ 9″ E longitude and 36° 33′ 55″ N latitude. The coordinates of the soil sampling points in the network (an area of 100 square kilometers) were determined, whereas the distance between these points was 900 m east–west and 1000 m north–south, covering good ranges of soil organic matter and texture, and land use. From this network and at a regular distance, 92 points were selected for measuring soil physical and chemical properties, 41 points for measuring soil available water content, and 55 points for measuring soil structural stability by the HEMC method.

Of the selected 92 points, 54 points had paddy field land use, 19 points were under citrus garden, 14 points had forest land use, and 5 points had pasture land use (Fig. 2). The studied soils were classified according to the USDA classification systems by Momtaz (2009). The paddy soils were classified as fine loamy, mixed, superactive, calcareous, thermic, Fluvaquentic Epiaquepts. The citrus garden soils were classified as fine loamy, mixed, semiactive, thermic, Fluvaquentic Eutrudepts and fine silty, mixed, active, thermic, Typic Hapludalfs. The forest soils were classified as fine, mixed, active, thermic, Mollic Paleudalfs and the pasture soils were classified as fine, mixed, superactive, thermic, Typic Argiudolls (Momtaz 2009).

From each point, soil samples were collected from 0 to 20 cm layer for determination of soil structural stability using the HEMC method and soil physical and chemical properties in the laboratory. In addition, intact samples were collected using stainless cylinders of 100 cm^3 for determination of soil available water and bulk density.

## Measurement of aggregate stability by the HEMC method

The HEMC method was used to characterize the aggregate stability in the studied soils (Collis-George and Figueroa 1984; Levy and Mamedov 2002; Mamedov and Levy 2013). The HEMC method is a sensitive method and can identify changes in soil aggregate stability in a broad range of soils from arid to humid zones (Pierson and Mulla 1989; Levy and Miller 1997; Levy and Mamedov 2002; Levy et al. 2003). In this method, two batches of aggregates are wetted slowly and quickly and their moisture characteristic curves at high matric potentials or low matric suctions (i.e., HEMCs) are measured under static (equilibrium) conditions (Fig. 3a). Since water retention at high energies (or high matric potentials) is mostly affected
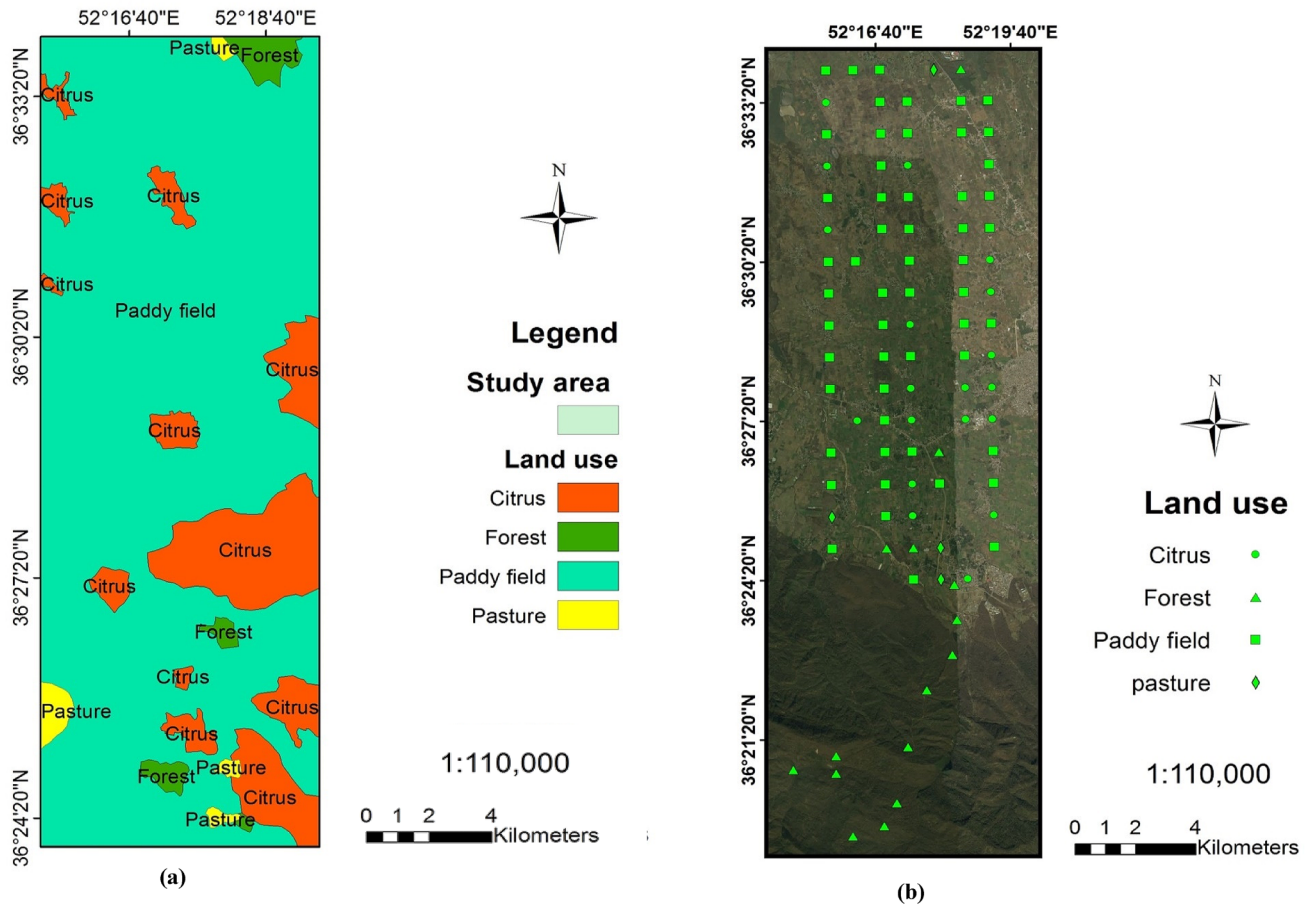
Fig. 2 Land use map (**a**) and soil sampling network (**b**) in the study area

Fig. 3 High energy moisture characteristics (HEMC) for slow- and fast-wetted aggregates (continuous curves show the fits of modified van Genuchten model) (**a**), and their corresponding specific water capacity ($C(\theta) = |\mathrm{d}\theta/\mathrm{d}h|$) curves and shrinkage lines, volume of drainable pores (VDP) and modal suction (h_{modal}) (**b**)
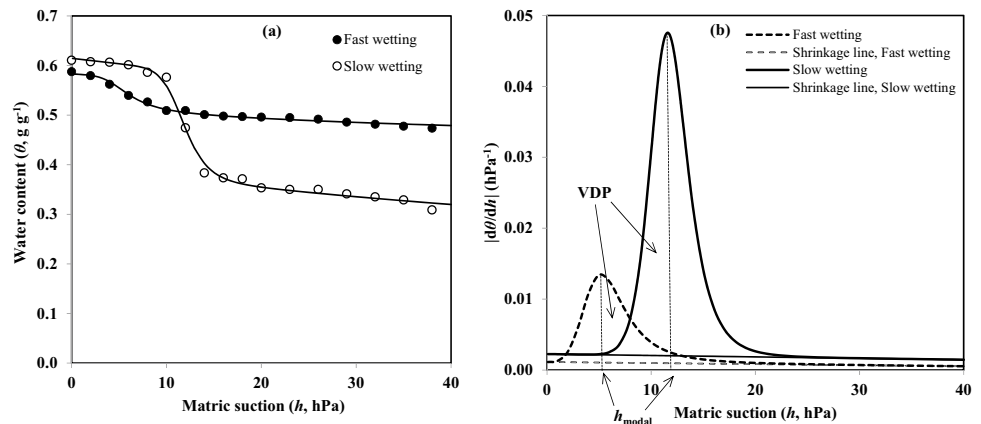
by soil structure, structural stability is characterized by quantifying the difference between HEMC of fast-wetted aggregates and that of slow-wetted ones. When the aggregates are wetted quickly, the air entrapment and uneven swelling might disrupt the aggregates compared to slow wetting. If the difference between HEMC of fast wetting and that of slow wetting (quantified by several structural stability indices as explained further) is small, the soil structure is stable and *visa versa*. The slope of HEMC for each wetting rate is drawn (Fig. 3b) and structural index (SI) is defined as the ratio of volume of drainable pores (VDP) to modal suction (h_{modal}) which are displayed schematically in Fig. 3b. The ratio of fast to slow SI values, called stability ratio (SR), is used to compare structural

stability on a relative scale of 0 to 1 (Collis-George and Figueroa 1984; Pierson and Mulla 1989; Levy and Mamedov 2002; Mamedov and Levy 2013; Hosseini et al. 2015).

Soil samples (with minimum destruction of aggregates) were gently sieved and fraction 0.5–1.0 mm was separated which was dominant in the studied soils. About 15–20 g of the 0.5–1.0 mm aggregates was poured into PVC cylinders with a diameter of 40 mm and a height of 5 mm. Two batches of aggregates (fast wetting and slow wetting) were

and Mulla (1989) pointed out that this adjustment has little influence on the n and α, but alters θ_r and θ_s, so that the model will accurately fit the legs of the HEMC data (Fig. 3a). The parameters were optimized by fitting Eq. (1) to the measured HEMC data using the nonlinear optimization technique of Microsoft Excel® Solver (Microsoft Corporation, Redmond, Washington State, US).

The specific water capacity function ($C(\theta) = |d\theta/dh|$, hPa^{-1}) was obtained by differentiation of Eq. (1) as follows (Levy and Mamedov 2002):

$$C(\theta) = |d\theta/dh| = (\theta_s - \theta_r)\left[1 + (\alpha h)^n\right]^{\left(\frac{1}{n} - 1\right)}\left(\frac{1}{n} - 1\right)(\alpha h)^n\left(n/\left\{h\left[1 + (\alpha h)^n\right]\right\}\right) + 2Ah + B \tag{2}$$

prepared for each soil. For the fast wetting pre-treatment, the samples were suddenly saturated with distilled water and were immersed in water for 24 h. For the slow wetting, the aggregates were placed in a sand box and were slowly saturated in the sequence of matric suctions (h) of 25, 23, 20, 18, 15, 13, 10, 7, 5, 2 and 0 hPa, with an equilibrium time of 60 min for each matric suction (Bearden 2001; Poch and Antunez 2011; Hosseini et al. 2015, 2017).

The HEMC curve of previously slow- and fast-wetted aggregates was measured in the h range of 0 to 50 hPa, with increment of 2 and 3 hPa for the h ranges of 0–20 and 20–50 hPa, respectively. The samples were weighed after equilibrium at each h value. Finally, the aggregates were oven-dried, and their gravimetric water content (θ, g g^{-1}) was calculated and drawn as a function of h (Fig. 3).

$$\theta(h) = \theta_r + (\theta_s - \theta_r)[1 + (ah)^n]^{\left(\frac{1}{n} - 1\right)} + Ah^2 + Bh + C \tag{1}$$

Aggregate stability indices were calculated by quantifying the differences in the HEMCs of fast and slow wetting pre-treatments. First, the HEMC data were modeled by the modified van Genuchten (1980) model (Levy and Mamedov 2002

where θ_r and θ_s are *pseudo*-residual and saturated water contents (g g^{-1}) that cannot be physically interpreted in terms of saturated and residual water contents (Pierson and Mulla 1989). The α (hPa^{-1}) and n (−) are empirical parameters which are related to the modal suction (at inflection point) and pore size distribution, respectively; and A (hPa^{-2}), B (hPa^{-1}), and C (g g^{-1}) are the quadratic coefficients. Quadratic coefficients were added to improve model fitting to the measured data because the original van Genuchten (1980) model predicts h_{modal} accurately, but does not produce accurate estimation of volume of drainable pores (VDP). Pierson

The volume of drainable pores (VDP, g g^{-1}), which is equal to the area under the $C(\theta)$ curve and above the pore shrinkage line ($2Ah + B$) (Fig. 3b), was calculated using Simpson's numerical method (Philip and Rabinowitz 1984; Hosseini et al. 2017). The pore shrinkage baseline represents the rate of water loss due to aggregate shrinkage rather than pore emptying (Collis-George and Figueroa 1984; Pierson and Mulla 1989). The VDP is theoretically equal to ($\theta_s - \theta_r$) as revealed in the data presented by Pierson and Mulla (1989).

The modal suction (h_{modal}, hPa, Fig. 3b) was calculated as h at the peak of $C(\theta)$, by equating the 2nd derivative of Eq. (1) to zero. The effect of $2A$ term [second term in the right hand of Eq. (2)] on the h_{modal} is negligible due to very low value of A; therefore the h_{modal} was approximated by the following equation (Hosseini et al. 2015):

$$h_{modal} \approx \frac{1}{\alpha}\left(\frac{n - 1}{n}\right)^{1/n} \tag{3}$$

For each wetting rate, a structural index (SI, hPa^{-1}) was calculated as the ratio of VDP to h_{modal}. For the two wetting methods of fast (FW) and slow wetting (SW), two SI values (SI$_{FW}$ and SI$_{SW}$, respectively) were defined. The stability ratio (SR) was calculated as the dimensionless ratio of SI$_{FW}$ to SI$_{SW}$ (Levy and Mamedov 2002):

$$SR = \frac{SI_{FW}}{SI_{SW}} \tag{4}$$

The SR varies between 0 (completely unstable) and 1 (completely stable) and was used to compare structural stability in different soils or land uses on a relative scale of 0 to 1 while higher SR, close to 1, shows greater soil structural stability (Collis-George and Figueroa 1984).

Moreover, the ratio of fast wetting VDP (VDP$_{FW}$) to slow wetting VDP (VDP$_{SW}$) was calculated and used as suggested by Levy and Miller (1997) and Levy and Mamedov (2002):

$$\text{VDPR} = \frac{\text{VDP}_{\text{FW}}}{\text{VDP}_{\text{SW}}} \tag{5}$$

The original van Genuchten (1980) model with Mualem's constraint ($m = 1 - 1/n$), Eq. (6), was also fitted to the measured HEMC data (θ vs. h pairs) to evaluate the HEMC method and indices in Dexter's S−theory (Dexter and Czyż 2008:

$$\theta(h) = \theta_r + (\theta_s - \theta_r)\left[1 + (\alpha h)^n\right]^{\left(\frac{1}{n}-1\right)} \tag{6}$$

The fitting parameters (θ_s, θ_r, α and n) were obtained using the nonlinear optimization technique of Solver Tool in Microsoft Excel®. Hosseini et al. (2015) introduced the slope of HEMC at inflection point (S_i) as an alternative structural stability index and suggested that the greater S_i means higher aggregate stability. This index is similar to Dexter's S index, but the derivatives of Eq. (6) were calculated based on normal scale of h (note that natural logarithmic scale of h was used in the original S−theory). Therefore, the slope at the inflection point of HEMC (S_i) was calculated as follows (Hosseini et al. 2015):

$$S_i = n\alpha(\theta_s - \theta_r)\left[\frac{n-1}{2n-1}\right]^{\left[\frac{2n-1}{n}\right]} \tag{7}$$

Then, the structural stability ratio (S_iR) similar to the SR was calculated using S_i values for HEMCs of slow- and fast-wetted aggregates according to Hosseini et al. (2015) by:

$$S_iR = \frac{S_{i\text{-FW}}}{S_{i\text{-SW}}} \tag{8}$$

Similar to SR, the dimensionless S_iR ranges from 0 to 1 and its greater values indicate better soil physical quality.

Measurement of soil available water

The intact soil samples were saturated and equilibrated at h values of 330 and 15,000 hPa in the pressure plate apparatus (Klute 1986). Volumetric water contents at h values of 330 and 15,000 hPa were measured, and available water (AW) was calculated by the following equation (Asgarzadeh et al. 2010; Kirkham 2014):

$$\text{AW} = \theta_{330} - \theta_{15000} \tag{9}$$

where θ_{330} and θ_{15000} are considered as the soil water contents at field capacity (θ_{FC}) and permanent wilting point (θ_{PWP}), respectively.

Measurement of soil physical and chemical properties

The percentage of soil primary particles (i.e., sand, silt, and clay) was determined by the hydrometer method and according to Stokes' law (Gee and Bauder 1986). Soil textural class was determined by the soil texture triangle of the US Department of Agriculture (USDA). Soil bulk density was determined using the intact core samples. The samples were dried at 105 °C in an oven for 24 h, and the bulk density was obtained by measuring the dry mass and the volume of the sampling cylinder (Blake and Hartge 1986).

Soil organic matter or OM (Walkly and Black 1934), calcium carbonate equivalent or CCE (Page et al. 1986), electrical conductivity (EC) and pH of saturated extract were measured using the wet oxidation method, back-titration method, EC-meter, and pH-meter, respectively.

Statistical analyses

Analysis of variance (ANOVA) was done using SAS software to investigate the effect of land use on the measured soil quality indicators. Mean comparisons were performed using the LSD test at $P < 0.05$. For the prediction purposes, each land use was considered to be one treatment with different replicates. Due to the diversity of soil properties, multivariable linear regression $\left(y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \varepsilon\right)$ was used, and the coefficients β_0, β_1, β_2 and β_3 were fitted to the data using the SAS software. It was hypothesized that in different land uses, different variables might influence the target variables; therefore, regression models were established separately for each land use and were evaluated with the Tukey test at probability levels of 5% and 1%.

Results and discussion

Statistical description of soil physical and chemical properties in the study area

Tables 1 and 2 list the general soil properties in the whole study area and paddy fields, respectively. Among the three primary fractions, silt had the highest amount in the study area. The dominant soil textural classes in the study area were clay loam and loam. The CCE varied in the range 0.5–27.2 kg 100 kg^{-1}, and soil pH varied from 6.94 to 7.95. The soil OM varied from 1.78 to 6.25 kg 100 kg^{-1}, indicating the moderate-to-good status of organic matter in the studied soils. The OM content is slightly lower in the paddy fields compared to the whole data. The EC of the studied soils varied from 0.29 to 1.83 dS m^{-1}, indicating that the studied soils are non-saline.

Table 1 Statistics of soil physical and chemical properties, structural stability indices and plant available water in the whole study area ($n = 92$ for physical and chemical properties, $n = 41$ for available water content and $n = 55$ for HEMC indices)

Parameter	Unit	Mean	Standard deviation	Skewness	Kurtosis	Minimum	Maximum
EC	dS m^{-1}	0.95	0.37	0.23	−0.22	0.29	1.83
pH	–	7.52	0.21	−0.38	−0.07	6.94	7.95
CCE	kg 100 kg^{-1}	11.4	5.47	0.31	0.47	0.5	27.2
OM	kg 100 kg^{-1}	3.56	1.1	0.79	−0.14	1.78	6.25
TN	kg 100 kg^{-1}	0.211	0.073	1.692	4.978	0.117	0.561
C/N ratio	–	10.02	1.49	3.47	19.2	7.7	19.5
ρ_b	g cm^{-3}	1.16	0.18	−0.46	0.24	0.65	1.50
Sand	kg 100 kg^{-1}	29.2	10.1	1.4	4.3	15.0	77.0
Silt	kg 100 kg^{-1}	41.0	7.6	−0.3	0.04	22.0	59.0
Clay	kg 100 kg^{-1}	30.2	9.7	1.0	0.2	15.0	56.0
OM/Clay ratio	–	0.14	0.07	1.47	2.72	0.03	0.44
θ_{330}	g g^{-1}	0.32	0.05	0.28	−0.49	0.23	0.42
θ_{15000}	g g^{-1}	0.15	0.04	0.3	−0.5	0.07	0.23
θ_{330}	cm^3 cm^{-3}	0.35	0.05	0.21	−0.97	0.25	0.45
θ_{15000}	cm^3 cm^{-3}	0.173	0.053	0.215	0.743	0.089	0.299
AW	cm^3 cm^{-3}	0.175	0.051	−0.162	−0.893	0.079	0.263
VDP$_{FW}$	g g^{-1}	0.105	0.076	1.23	1.25	0.013	0.330
VDP$_{SW}$	g g^{-1}	0.286	0.083	−0.21	−0.23	0.119	0.453
VDPR	–	0.342	0.231	1.052	1.431	0.005	1.042
$h_{modal-FW}$	hPa	9.7	3.6	0.2	0.2	3.8	20.9
$h_{modal-SW}$	hPa	10.9	0.9	−0.1	0.2	8.6	13.3
h_{modal}R	–	0.87	0.37	−0.01	−0.96	0.28	1.69
SI$_{FW}$	hPa^{-1}	0.183	0.0167	2.532	6.784	0.004	0.083
SI$_{SW}$	hPa^{-1}	0.058	0.019	−0.110	−0.713	0.017	0.096
SR	–	0.397	0.250	0.352	−0.454	0.010	0.980
S_iR	–	0.275	0.165	–	–	0.067	0.913

EC Electrical conductivity of saturated soil paste, *pH* pH of saturated soil paste, *CCE* Calcium carbonate equivalent, *OM* Organic matter content, *TN* Total nitrogen content, ρ_b Bulk density, θ_{330} Water content at field capacity, θ_{15000} Water content at permanent wilting point, *AW* Available water, *VDP* Volume of drainable pores, h_{modal} Modal suction, *SI* Structural index, SR and S_iR Stability ratios calculated using the modified van Genuchten and van Genuchten models, respectively

The effect of land use on soil physical and chemical properties

The ANOVA results showed that the effect of land use on EC, OM, C/N ratio and clay content was significant at $P < 0.01$, and on the CCE and OM/Clay ratio was significant at $P < 0.05$, but the effect of land use on pH, TN, ρ_b, sand and silt contents was not significant (Table 3).

Figure 4 shows the soil pH means among the land uses in the study area. There was no significant difference of pH values among the land uses. In this study, a significant negative correlation ($r = −0.43$) was found between the soil OM and pH. Organic materials have acidic nature due to the presence of acidic functional groups such as carboxyl, OH and phenol on their surfaces. Soil organic matter, root presence and carbon dioxide production would lower the soil pH. Land use had a significant effect on soil OM (Fig. 4). The highest value of soil OM was observed in forest, followed by pasture, citrus garden and paddy field, but the difference was

only significant between the forest and paddy field. It seems that in the soils under grass cover and pasture, the topsoil is relatively thick and dark due to organic inputs of numerous fibrous roots. Moreover, the lifetime of grassy plants is short, and the dead roots of plants are annually returned and easily decomposed/added to the soil organic matter. Similarly Alidoust et al. (2018) found that mean OC contents in the pasture, forest, rain-fed and irrigated farmlands were 10.3, 20.2, 9.2 and 10.1 g kg^{-1}, respectively.

In the studied pastures, the soil OM was high due to lack of livestock grazing and grass-type vegetation which is returned to the soil. In the forest soils, the litters and organic materials would accumulate on the soil surface but they are slowly decomposed and incorporated into the topsoil. The soil OM was lower in the citrus gardens compared to forest (Fig. 4), owing to the low density of trees and their permanent greenery. The soil OM was lowest in the paddy fields compared to other land uses because burning straw after harvest had reduced the residues entry into the soil, being

Table 2 Statistics of soil physical and chemical properties, structural stability indices and plant available water in the paddy fields ($n = 54$ for physical and chemical properties, $n = 23$ for available water content and $n = 28$ for HEMC indices)

Parameter	Unit	Mean	Standard deviation	Minimum	Maximum
EC	dS m^{-1}	1.011	0.356	0.300	1.830
pH	–	7.538	0.187	7.030	7.930
CCE	kg 100 kg^{-1}	12.276	5.924	0.500	27.200
OM	kg 100 kg^{-1}	3.432	1.071	1.780	6.160
TN	kg 100 kg^{-1}	0.199	0.058	0.117	0.343
C/N	–	9.870	1.127	7.700	15.200
ρ_b	g cm^{-3}	1.174	0.155	0.800	1.500
Sand	kg 100 kg^{-1}	28.8	11.5	15.0	77.0
Silt	kg 100 kg^{-1}	41.0	7.9	22.0	59.0
Clay	kg 100 kg^{-1}	30.2	9.6	16.0	56.0
OM/Clay ratio	–	0.12	0.06	0.03	0.27
θ_{330}	g g^{-1}	0.32	0.03	0.26	0.39
θ_{15000}	g g^{-1}	0.14	0.04	0.09	0.22
θ_{330}	cm^3 cm^{-3}	0.35	0.06	0.27	0.45
θ_{15000}	cm^3 cm^{-3}	0.177	0.053	0.090	0.299
AW	cm^3 cm^{-3}	0.177	0.055	0.079	0.236
VDP$_{FW}$	g g^{-1}	0.105	0.076	0.013	0.330
VDP$_{SW}$	g g^{-1}	0.286	0.083	0.119	0.453
VDPR	–	0.381	0.262	0.009	1.042
$h_{modal\text{-}FW}$	hPa	9.516	3.995	3.835	20.919
$h_{modal\text{-}SW}$	hPa	11.148	0.878	9.286	13.320
$h_{modal}R$	–	0.839	0.363	0.292	1.688
SI$_{FW}$	hPa^{-1}	0.020	0.018	0.006	0.084
SI$_{SW}$	hPa^{-1}	0.057	0.022	0.017	0.097
SR	–	0.457	0.271	0.015	0.980
S_iR	–	0.323	0.192	0.069	0.913

EC Electrical conductivity of saturated soil paste, *pH* pH of saturated soil paste, *CCE* Calcium carbonate equivalent, *OM* organic matter content, *TN* Total nitrogen content, ρ_b Bulk density, θ_{330} Water content at field capacity, θ_{15000} Water content at permanent wilting point, *AW* Available water, *VDP* Volume of drainable pores, h_{modal} Modal suction, *SI* Structural index, SR and S_iR Stability ratios calculated using the modified van Genuchten and van Genuchten models, respectively

consistent with the findings of Hajabbasi et al. (2001). Generally lower OM content in the paddy fields can be attributed to breakdown of aggregates due to intensive cultivation practices and exposure of physically protected organic materials to oxidation processes. Besides, burning plant residues, harvesting and water erosion are considered effective on soil organic matter (Martinez et al. 2008).

Land use did not have a significant effect on the soil bulk density (ρ_b), but the lowest ρ_b values were found in the forest and pasture, whereas the highest ρ_b values were observed

in the citrus garden and paddy field (Fig. 4). Low ρ_b value in the forest can be attributed to high OM content in the forest soils (i.e., abundance of macropores), stable structure, and high porosity similar to the findings of Kelishadi et al. (2014). High ρ_b in the citrus garden can be related to poor soil structure and destruction of pore system due to machinery traffic during harvesting. Likewise Reszkowska et al. (2011) reported that ρ_b increased by increasing the grazing intensity. Besides, Mofidi et al. (2012) investigated the effect of pasture conditions (including low, medium, and severe grazing intensities) on soil physical properties in Sahand Mountain Range in Iran. They found that severe grazing increased the soil ρ_b due to combined effects of low OM and compaction by livestock tramping. Therefore, soil ρ_b in the pasture with low grazing was significantly lower than in the others. However, in the protected pastures, low ρ_b was related to high OM and low soil compaction. Abu-Hashim (2011) reported that high ρ_b in the arable lands is associated with poor structure and degradation of soil pore system, which could be the result of high machinery traffic during planting and harvesting. In the paddy field soils, the small number of macropores and the high number of micropores are found, and the soil ρ_b would increase as a result of puddling.

The soil EC varied in the range 0.29 to 1.83 dS m^{-1}, indicating that the soils are non-saline in the study area (Table 1). A significant difference was noticed between the means of EC in the paddy field and citrus garden, and forest and pasture land uses (Fig. 4). The highest EC belonged to the paddy field, which is probably related to the solvation of some multivalent elements under reducing conditions. Ponnamperuma (1978) reported that increased EC in the paddy field soil is probably due to the conversion of Fe and Mn oxides to soluble ions of Fe^{2+} and Mn^{2+} under reducing conditions. Accordingly, Akbari et al. (2011) concluded that the soil EC under rice cultivation is higher than that under other land uses in Isfahan, Iran. Moreover, Boroumand et al. (2014) showed that soil EC in the paddy fields was significantly higher than those in the forest, rainfed farming, and garden land uses. High soil EC in the citrus garden land use (Fig. 4) can be due to the fertilizers application or irrigation with poor-quality waters in accord with the findings of Boroumand et al. (2014).

No significant difference was found between the land uses in terms of sand percentage (Table 3). It should be noted that all changes in the soil texture cannot be linked to different land uses, but the location and slope of each land use is effective as well. However, citrus gardens had the highest sand percentage owing to frequent irrigation by gardeners and selective washing and erosion of smaller particles; thus

Table 3 Means' comparisons of soil physical and chemical properties as affected by land use types

Means of land use groups

Land use	EC	pH	CCE	OM	TN	C/N	ρ_b	Sand	Silt	Clay	OM/Clay ratio
Forest	0.673[ab]	7.508[a]	7.555[b]	4.205[a]	0.255[a]	11.858[a]	1.095[a]	28.846[a]	36.928[b]	36.166[b]	0.165[ab]
Pasture	0.526[b]	7.386[a]	15.7[a]	3.78[ab]	0.226[ab]	9.86[b]	1.150[a]	26.33[a]	41.33[ab]	39.00[a]	0.221[a]
Citrus garden	1.01[a]	7.526[a]	10.668[ab]	3.488[ab]	0.218[ab]	9.30[b]	1.174[a]	31.105[a]	34.842[a]	25.052[b]	0.143[b]
Paddy field	1.011[a]	7.537[a]	12.276[ab]	3.432[b]	0.199[b]	9.869[b]	1.173[a]	28.811[a]	41.094[ab]	30.240[b]	0.125[b]

EC Electrical conductivity of saturated soil paste, *pH* pH of saturated soil paste, *CCE* Calcium carbonate equivalent, *OM* organic matter content, *TN* Total nitrogen content, ρ_b Bulk density; In each column, numbers with different letters indicate a significant difference (LSD, $P < 0.05$)
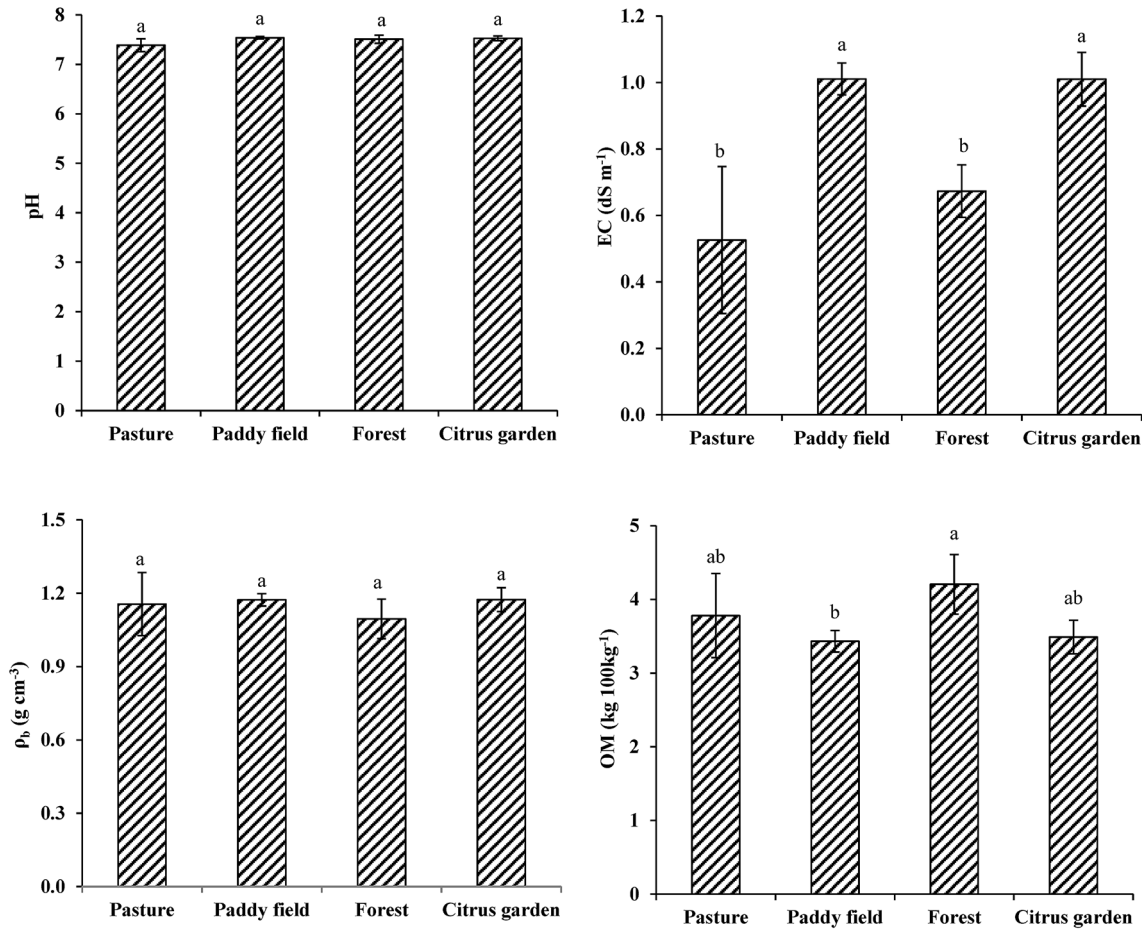
Fig. 4 Means' comparisons of soil pH, electrical conductivity (EC), bulk density (ρ_b) and organic matter content (OM) as affected by land uses; different letters indicate significant differences on 5% statistical level based on Duncan test; ± standard errors are shown on the bars

larger particles remained in the topsoil. For this reason, the clay percent in the topsoil under the citrus land use was significantly lower than that of other land uses. Hassann-ezhad et al. (2008) stated that clay minerals in the paddy fields have been influenced by parent materials more than by oxidation–reduction cycles. Their results showed that poor drainage and base-rich parent materials could affect the formation and transformation of minerals. They stated

that anthropogenic aquic condition induced the formation of smectites.

Under aquic conditions, high concentration of cations like K^+ may induce the formation of pedogenic smectite. Smectites are more stable in poorly drained conditions (Dixon et al. 1989). Boroumand et al. (2014) reported the highest amount of clay in the paddy field land use compared to forest and garden land uses. The amount of soil silt in the forest

was significantly lower than those in the other land uses (Table 3).

The effect of land use on the soil C/N ratio was significant (Table 3). The highest C/N ratio was calculated for the forest land use which was significantly different from other land uses. The higher C/N ratio in the forest land use can be related to greater input of organic materials (Alemayehu et al. 2016). The means of C/N ratio were 9.9 and 10.2 in the paddy fields and in the whole study area, respectively (see Tables 1 and 2). The soil C/N ratio shows the combined effects of C and N cycles and the quality of soil organic matter, because it controls the nitrification and decomposition processes. Low C/N ratio increases the inorganic N concentration by accelerating the N mineralization rate (Dai et al. 2019). Dai et al. (2019) showed that soil C/N ratio had a significant and direct negative effect on the rice yield; the C/N ratio of 10.1–10.2 corresponded to rice yield of 6800 kg ha^{-1}–7000 kg ha^{-1}.

Mean values of CCE were 11.4 and 12.3 kg 100 kg^{-1} in the whole study area and paddy fields, respectively (see Tables 1 and 2). Significant difference was found between pasture and forest land use in terms of CCE (see Table 3). Celik (2005) related the low level of CCE in forest soils compared to cropland to the carbonate transfer and formation of secondary carbonates in the subsoil in forest. Significant and positive correlations were observed between CCE and S_iR in both the whole study area and the paddy fields (see Tables 5 and 6) because calcium carbonate can act as a cementing and flocculating agent, having positive effect on soil structural stability. A significant negative correlation was found between θ_{15000} and CCE in both the whole study area and the paddy fields in agreement with Khodaverdilloo et al. (2011) who reported an increase in the θ_{15000} with a decrease in carbonate content. The effect of carbonates on soil water retention would depend on the type these compounds as well. Primary carbonates (sand-sized ones) have low water holding capacity but secondary carbonates (silt- and clay-sized ones) have high water retention, especially at high matric suctions (Motallebi et al. 2011). Asgari Hafshejani and Jafari (2017) found that AW was affected by the size and concentration of carbonates; they introduced carbonate content as an important independent variable effective on θ_{15000}.

Correlation between HEMC stability indices, organic matter and clay content

The HEMC stability indices including VDPR, SR, and S_iR had significant positive correlations with the OM and $\frac{OM}{Clay}$ ratio (Tables 5 and 6). In addition, the VDPR had a significant positive correlation with the OM, $\frac{OM}{Clay}$ ratio, SR, and

S_iR. Among the factors affecting soil structural stability, organic matter is of particular importance. Organic matter can protect aggregates against mechanical forces and water through the formation of cationic bonds with clay particles, neutralizing the surface charges of clay particles by organic ions, and creating hydrophobic coatings. The positive correlation between VDPR and $\frac{OM}{Clay}$ ratio indicates that soil OM irrespective of soil texture (as quantified by the relative quantity $\frac{OM}{Clay}$) would increase the aggregate stability. It means that by increasing the $\frac{OM}{Clay}$ ratio, a higher amount of clay is complexed with OM, thus increasing the soil structural stability. Dexter et al. (2008) found that organic carbon and clay have a significant effect on some important soil physical properties, including structural stability. They showed that in the agricultural soils, OC is more concentrated in the form complexed with clay (COC), and soil structural stability is mainly controlled by the amount of COC rather than by the total OC content. Our findings are consistent with the results of Hosseini et al. (2015, 2017) who found a strong correlation between soil structural stability indices and $\frac{OM}{Clay}$ ratio.

Significant negative correlations were found between SI$_{FW}$ and clay content in the whole study area and in the paddy fields (with smectitic clay minerals) (Tables 5 and 6). In addition, there was a significant negative correlation between SR and clay content in the paddy fields land use (Table 6). De-Campos et al. (2007) showed that in six different soils saturated for various periods, the rapid soil saturation reduced the SR and structural stability due to shrinking and swelling mechanisms and destruction of aggregates. It is likely that rapid water saturation of soil with a mixed clay mineralogy at the commencement of the incubation period resulted in slaking and swelling mechanisms, thus leading to the breakdown of aggregates. Earlier studies have shown that slaking and swelling play a crucial role in aggregate breakdown when the soil is wetted quickly. Slaking happens at the beginning of saturation when the soil is wetted and the air entrapped inside aggregates is compressed, resulting in aggregate breakdown. Slaking does not play an important role as soon as the initial soil water content rises and the amount of entrapped air drops (Truman et al. 1990). Therefore, slaking should not have been significant in the present study after a few hours of saturation. Swelling may become important when the soil water content increases (Sumner 1992; Le Bissonnais 1996). Swelling will become important as the amount of expandable 2:1 clay minerals, such as smectites, in the soil increases.

In the paddy fields land use, there were significant correlations between SI$_{FW}$ and $\frac{OM}{Clay}$ ratio, between h_{modal} and OM, and between h_{modal} and $\frac{OM}{Clay}$ ratio (Table 6). The correlations between SI$_{FW}$ and $\frac{OM}{Clay}$ ratio were significant regardless

of land uses. De-Campos et al. (2007) found that in the saturated soils, SR decreased by decreasing the OC, and that the highest SR was related to the highest OC content in the cultivated soils. The significant positive correlation between SI_{FW} and $\frac{OM}{Clay}$ ratio is consistent with the findings of De-Campos et al. (2007) and Hosseini et al. (2015). Organic matter could bond soil particles and hydrophobic coatings reduce wetting rate of the aggregates. It, therefore, decreases their sensitivity to slaking during wetting. However, the probable combined effects of clay and organic matter contents could expose higher structural stability than that of clay content or organic matter alone in the fast wetting (De-Campos et al. 2007). In addition, there was a significant positive correlation between VDPR and EC (Tables 5 and 6), indicating that salinity is a driver for structural stability due to flocculation of soil particles by soluble cations.

The effect of land use on HEMC stability indices

Figure 5 presents examples of HEMCs and corresponding specific water capacity ($|d\theta/dh|$) curves showing the effects of studied four land uses on soil aggregate stability. Figure 5a, b shows the measured HEMC data and the curves predicted by the modified van Genuchten model in the fast- and slow-wetted pre-treatments, respectively. The fits of the modified van Genuchten model to the HEMC data were excellent ($R^2 = 0.99$). The ANOVA results revealed that land use type did not have significant effects on the VDPR, SR, S_iR, and $h_{modal}R$ (see Table 4). However, the highest values of VDPR, SR and $h_{modal}R$ were observed in the forest land use. The effect of forest land use on the HEMC was smaller for the slow-wetted aggregates than for the fast-wetted aggregates. The VDP_{Fw} and VDPR values were higher in the forest than other land uses (see Table 4 and Fig. 5) and the h_{modal} was greater for the fast-wetted aggregates in the
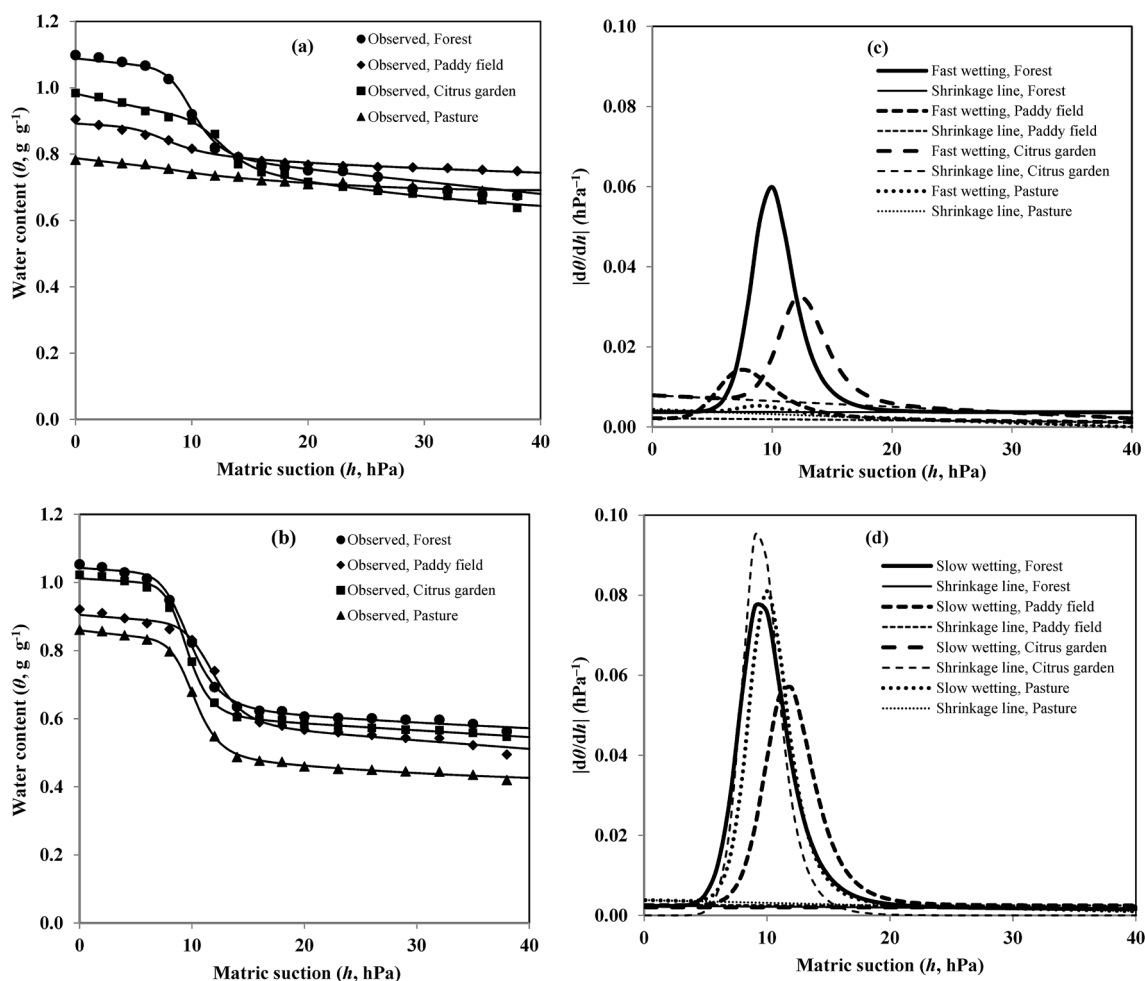
Fig. 5 Examples of high energy moisture characteristics (HEMC) and corresponding specific water capacity ($|d\theta/dh|$) curves in the studied four land uses: **a, b** measured HEMCs and predicted continuous curves (by the modified van Genuchten model) in fast wetting and slow wetting pre-treatments, respectively, and **c, d** corresponding specific water capacity ($|d\theta/dh|$) curves with shrinkage lines for (a) and (b)

Table 4 Means' comparisons of soil structural stability indices of HEMC method as affected by land use types

Means of land use groups

Land use	VDP_{FW}	VDP_{SW}	VDPR	$h_{modal\text{-}FW}$	$h_{modal\text{-}SW}$	$h_{modal}R$	SI_{FW}	SI_{SW}	SR	S_iR
Forest	0.146a	0.341a	0.385a	9.47a	10.40a	0.97a	0.016a	0.033a	0.483a	0.281a
Pasture	0.057a	0.261a	0. 266a	9.13a	11.03a	0.852a	0.0079a	0.025a	0.426a	0.366a
Citrus garden	0.116a	0.310a	0.360a	9.30a	10.83a	0.87a	0.012a	0.029a	0.349a	0.379a
Paddy field	0.110a	0.281a	0.367a	8.99a	10.52a	0.85a	0.012a	0.027a	0.46a	0.375a

VDP: volume of drainable pores, h_{modal}: modal suction, SI: structural index, SR and S_iR: stability ratios calculated using the modified van Genuchten and van Genuchten models, respectively; In each column, numbers with different letters indicate a significant difference (LSD, $P < 0.05$)

Table 5 Pearson's correlation between soil structural stability indices and pore fractions calculated by modified van Genuchten model, plant available water and physical and chemical properties in all of the studied soils

	EC	pH	CCE	OM	TN	C/N	ρ_b	Clay	OM/Clay ratio
ρ_b	0.390***	0.453***	−0.004 ns	0.479***	0.663***	0.078 ns	1	−0.013 ns	−0.498***
θ_{330}	0.016 ns	−0.132 ns	−0.034 ns	0.501***	0.383**	0.139 ns	0.266 ns	0.121 ns	0.233 ns
θ_{15000}	0.132 ns	−0.074 ns	−0.406**	0.209 ns	0.415**	0.163 ns	0.210 ns	0.569***	−0.225 ns
$\theta_{330(vol.)}$	0.037 ns	−0.056 ns	0.060 ns	0.003 ns	0.035 ns	0.161 ns	0.340*	0.154 ns	−0.100 ns
$\theta_{15000(vol.)}$	0.319*	0.044 ns	0.266 ns	0.035 ns	0.109 ns	0.055 ns	0.283 ns	0.527***	−0.373**
AW	0.230 ns	−0.251 ns	0.243 ns	0.236 ns	0.181 ns	0.174 ns	0.134 ns	−0.289 ns	0.325 *
VDP_{FW}	0.405***	−0.210 ns	0.108 ns	0.404***	0.535***	0.056 ns	0.331*	−0.507***	0.672***
VDP_{SW}	0.012 ns	−0.274*	−0.259 ns	0.435***	0.520***	0.083 ns	0.060 ns	0.196 ns	0.198 ns
VDPR	0.452***	−0.164 ns	0.222 ns	0.368***	0.416***	0.143 ns	0.250 ns	−0.543***	0.670***
$h_{modal\text{-}FW}$	0.010 ns	−0.163 ns	−0.078 ns	0.349**	0.244 ns	0.089 ns	0.153 ns	0.188 ns	0.188 ns
$h_{modal\text{-}SW}$	0.083 ns	0.172 ns	0.175 ns	0.206 ns	0.376***	0.010 ns	0.122 ns	−0.157 ns	−0.081 ns
$h_{modal}R$	0.013 ns	−0.176 ns	0.043 ns	0.476***	0.352**	0.209 ns	0.135 ns	−0.087 ns	0.381***
SI_{FW}	0.270*	−0.095 ns	0.260 ns	0.347**	0.356**	0.047 ns	0.084 ns	−0.411***	0.512***
SI_{SW}	0.020 ns	−0.236 ns	0.348**	0.297*	0.414***	0.080 ns	0.105 ns	0.232 ns	0.062 ns
SR	0.375***	0.008 ns	0.173 ns	0.067 ns	0.035 ns	0.001 ns	0.059 ns	−0.468***	0.289*
S_iR	0.346**	0.013 ns	0.350**	0.219 ns	0.194 ns	0.104 ns	0.136 ns	−0.568***	0.525***

EC Electrical conductivity of saturated soil paste, *pH* pH of saturated soil paste, *CCE* Calcium carbonate equivalent, *OM* Organic matter content, *TN* Total nitrogen content, ρ_b Bulk density, θ_{330} Water content at field capacity, θ_{15000} Water content at permanent wilting point, *AW* Available water, *VDP* Volume of drainable pores, h_{modal} Modal suction, *SI* Structural index, SR and S_iR Stability ratios calculated using the modified van Genuchten and van Genuchten models, respectively

ns, *, ** and *** stand for non-significant, significant at 0.05, 0.01 and 0.001 probability levels, respectively

forest (Table 4). The water retention of the slow-wetted and fast-wetted aggregates was greater in the forest than other land uses in the *h* range of 015 hPa (pore size > 200 μm) and 2040 hPa (pore size < 150 μm) (Fig. 5a, b).

In the paddy fields, iron and manganese minerals such as ferrihydrate, iron and manganese oxides, as strong agents of aggregates, would be dissolved and their bonds with clay particles could increase the dispersion due to the presence of smectitic clays under reducing conditions. Therefore, it was expected that structural stability in the paddy fields would decrease in comparison with other land uses. Saedi et al. (2021) showed that biological and chemical aggregation agents were reduced, and soil structural degradation was intensified under oxygen-limited conditions. However, the correlations of all stability indices with OM (see Tables 5 and 6) and its dominant effect revealed a different result in this study. In line with the findings of this study, Boroumand et al. (2014) reported that forest had the highest soil structural stability due to high amounts of OM compared to rainfed farming and citrus garden land uses.

The effect of land use on field capacity, permanent wilting point, and available water

Soil water content is a dynamic parameter under the influence of various land uses, affecting several soil physical and chemical properties and plant growth (Torabi Golsefidi et al. 2001). The results revealed that the type of land use had

Table 6 Pearson's correlation between soil structural stability indices and pore fractions calculated by modified van Genuchten model, plant available water and physical and chemical properties in the paddy fields

	EC	pH	CCE	OM	TN	C/N	ρ_b	Clay	OM/Clay ratio
ρ_b	−0.429[***]	0.476[***]	−0.176 ns	−0.562[***]	−0.693[***]	0.016 ns	1	0.025[ns]	−0.504[***]
θ_{330}	0.130 ns	−0.384 ns	0.187 ns	0.563[**]	0.668[***]	−0.033 ns	−0.503[*]	0.007 ns	0.385[ns]
θ_{15000}	−0.066 ns	−0.182 ns	−0.543[***]	0.210 ns	0.505[**]	−0.267 ns	−0.286 ns	0.613[***]	−0.230 ns
$\theta_{330(vol.)}$	0.115 ns	−0.220 ns	−0.087 ns	0.032 ns	0.129 ns	0.070 ns	0.250 ns	0.161 ns	−0.154 ns
$\theta_{15000(vol.)}$	−0.218 ns	0.029 ns	−0.430[*]	−0.153 ns	0.043 ns	−0.261 ns	0.145 ns	0.502[**]	−0.461[*]
AW	0.324 ns	−0.243 ns	0.330 ns	0.179 ns	0.084 ns	0.315 ns	0.104 ns	−0.326 ns	0.295 ns
VDP_FW	0.417[*]	−0.299 ns	0.195 ns	0.560[***]	0.564[***]	0.303 ns	−0.585[***]	−0.480[**]	0.659[***]
VDP_SW	−0.043 ns	−0.208 ns	−0.288 ns	0.388[*]	0.469[**]	0.128 ns	−0.077 ns	0.276 ns	0.120 ns
VDPR	0.471[**]	−0.251 ns	0.320 ns	0.555[***]	0.535[***]	0.313 ns	−0.398[*]	−0.590[***]	0.734[***]
$h_{modal-FW}$	−0.045 ns	−0.143 ns	−0.117 ns	0.345 ns	0.376[*]	0.069 ns	−0.278 ns	0.198 ns	0.204 ns
$h_{modal-SW}$	0.294 ns	−0.151 ns	0.127 ns	0.012 ns	0.030 ns	0.033 ns	−0.071 ns	−0.236 ns	0.129 ns
$h_{modal}R$	−0.058 ns	−0.077 ns	0.064 ns	0.495[***]	0.411[*]	0.329 ns	−0.201 ns	−0.136 ns	0.478[**]
SI_FW	0.138 ns	−0.022 ns	0.260 ns	0.501[***]	0.43[*]	0.271 ns	−0.272 ns	−0.442[*]	0.601[***]
SI_SW	−0.124 ns	−0.168 ns	−0.432[*]	0.226 ns	0.367[*]	−0.034 ns	−0.118 ns	0.350 ns	−0.051 ns
SR	0.472[**]	−0.148 ns	0.188 ns	0.003 ns	0.067 ns	0.025 ns	0.002 ns	−0.479[**]	0.238 ns
S_iR	0.219 ns	0.048 ns	0.388[*]	0.363 ns	0.263 ns	0.329 ns	−0.195 ns	−0.601[***]	0.603[***]

EC Electrical conductivity of saturated soil paste, *pH* pH of saturated soil paste, *CCE* Calcium carbonate equivalent, *OM* organic matter content, *TN* Total nitrogen content, ρ_b Bulk density, θ_{330} Water content at field capacity, θ_{15000} Water content at permanent wilting point, *AW* Available water, *VDP* Volume of drainable pores, h_{modal} Modal suction, *SI* Structural index, *SR* and S_iR Stability ratios calculated using the modified van Genuchten and van Genuchten models, respectively

ns, *, ** and *** stand for non-significant, significant at 0.05, 0.01 and 0.001 probability levels, respectively

Table 7 Means' comparisons of field capacity, permanent wilting point, and plant available water as affected by land use types

Mean of land use groups

Land use	θ_{330}	θ_{15000}	$\theta_{330(vol.)}$	$\theta_{15000(vol.)}$	AW
Forest	0.413[a]	0.145[a]	0.355[a]	0.172[a]	0.182[a]
Pasturage	0.287[b]	0.170[a]	0.335[a]	0.222[a]	0.155[a]
Citrus	0.287[b]	0.134[a]	0.332[a]	0.159[a]	0.173[a]
Paddy field	0.327[b]	0.149[a]	0.355[a]	0.177[a]	0.177[a]

θ_{330} Water content at field capacity, θ_{15000} Water content at permanent wilting point, *AW* Available water; In each column, numbers with different letters indicate a significant difference (LSD, $P < 0.05$)

only a significant effect ($P < 0.01$) on field capacity (θ_{330}). The highest value of θ_{330} (i.e., 0.42 g g^{-1}) was observed in the forest land use with a fine soil texture, while its lowest value (i.e., 0.28 g g^{-1}) was noticed in the citrus garden land use with a medium soil texture (see Table 7). There was a significant positive correlation between θ_{330} (g g^{-1}) and OM in all the land uses and in the paddy fields (see Tables 5 and 6) showing the positive effect of OM on soil structure and formation of mesopores. Furthermore, a significant positive correlation was observed between the permanent wilting point (θ_{15000}, g g^{-1}) and clay content (see Tables 5 and 6), which can be due to the positive effect of clay on the

formation of micropores and adsorbed water (Torabi Golsefidi et al. 2001).

Forest land use was significantly different from other land uses in terms of θ_{330} with gravimetric unit (Table 7). This finding can be explained by the fact that forest soils have higher OM than garden and agricultural soils. Organic matter affects various soil physical characteristics such as porosity and bulk density (Molaeinasab et al. 2018). Previous studies indicated that an increase in the OC could increase soil hydro-structural stability, porosity and water retention (Boivin et al. 2009). Paddy fields, in the second rank after the forest land use, had the highest θ_{330} (g g^{-1}) and θ_{15000} (g g^{-1}) values (Table 7), which can be attributed to the higher clay (neoformation of smectites in the soil solution under reducing conditions) and 2:1 expandable smectites in the paddy field soils as explained by Torabi Golsefidi et al. (2001).

The lower value of θ_{330} (g g^{-1}) in the citrus garden (Table 7) can be due to the fact that microbial decomposition of soil organic matter increases upon cultivation. Mineralization of OC and release of CO_2 can cause the removal of organic carbon from the soil. Besides, deeper soil layers with less OC content are mixed with the surface soil containing higher OC content during moldboard plowing. Therefore, OC of the surface soil decreases compared to its initial state, resulting in lower soil water retention.

Table 8 Pearson's correlation between soil structural stability indices and pore fractions calculated by modified van Genuchten model and plant available water in all of the studied soils

	θ_{330}	θ_{15000}	$\theta_{330(vol.)}$	$\theta_{15000(vol.)}$	AW
VDP_{FW}	0.104 [ns]	−0.082 [ns]	−0.065 [ns]	−0.292 ns	0.342[*]
VDP_{SW}	0.092 ns	0.420[*]	0.276 ns	0.241 ns	0.182 ns
VDPR	0.210 ns	−0.297 ns	−0.02 ns	−0.353[*]	0.382[*]
$h_{modal-FW}$	0.305 ns	0.265 ns	0.028 ns	0.066 ns	0.089 ns
$h_{modal-SW}$	−0.010 ns	−0.239 ns	0.002 ns	−0.169 ns	0.070 ns
$h_{modal}R$	0.179 ns	0.092 ns	−0.009 ns	−0.048 ns	0.210 ns
SI_{FW}	0.140 ns	−0.124 ns	0.007 ns	−0.145 ns	0.289 ns
SI_{SW}	0.034 ns	0.339 ns	0.196 ns	0.149 ns	0.101 ns
SR	0.110 ns	−0.307 ns	0.090 ns	−0.213 ns	0.235 ns
S_iR	0.251 ns	−0.367[*]	−0.120 ns	−0.279 ns	0.272 [ns]

θ_{330} Water content at field capacity, θ_{15000} Water content at permanent wilting point, *AW* Available water, *VDP* Volume of drainable pores, h_{modal} Modal suction, *SI* Structural index, *SR* and S_iR Stability ratios calculated using the modified van Genuchten and van Genuchten models, respectively

ns and * stand for non-significant and significant at 0.05 probability level, respectively

Relationships between soil structural stability indices, θ_{330}, θ_{15000} and AW

Correlation coefficients between soil structural stability indices, θ_{330}, θ_{15000} and AW in all the land uses and paddy fields are presented in Tables 8 and 9, respectively. A significant negative correlation was found between VDPR and volumetric θ_{15000}, which is probably due to indirect effect of clay (Table 8). The higher the amount of clay, the lower will be the structural stability and the higher will be the water content at wilting point. A negative correlation between VDPR and volumetric θ_{15000} was also noticed in the paddy fields

land use (Table 9), which can be attributed to the presence of clay since there was a significant negative correlation between VDPR and clay (Table 6).

There was a significant positive correlation between VDP_{SW} and gravimetric θ_{15000} in the whole study area (Table 8), and a stronger correlation was found in the paddy fields land use (Table 9). Moreover, there was a significant positive correlation between AW and structural stability indices of VDP_{FW} and VDPR, which can be attributed indirectly to the positive effect of organic matter on aggregate stability and available water (Table 8). A significant positive correlation was found between VDPR and saturated water content in the paddy fields land use. In addition, a significant negative correlation was obtained between S_iR and volumetric θ_{15000} in this land use (Table 9).

Pedotransfer functions for predicting HEMC stability indices and available water

It is possible to measure soil structural stability indices and hydraulic properties directly in the laboratory. Indirect methods or predictive techniques can be considered as alternatives to direct methods. These indirect methods are called pedotransfer functions (PTFs) for prediction of soil properties. PTFs show the relationships between available information (easily available) and the information which a researcher needs (hardly available) (Wösten et al. 2001; Pachepsky and Rawls 2004; Mosaddeghi and Mahboubi 2011).

Multiple linear regression relationships for the prediction of VDPR in different land uses in the study area are derived as follows:

$$VDPR = -0.037 + 2.90 \frac{OM}{Clay} \quad R^2 = 0.53** \quad (10)$$

Table 9 Pearson's correlation between soil structural stability indices and pore fractions calculated by modified van Genuchten model and plant available water in the paddy fields

	θ_{330}	θ_{15000}	$\theta_{330(vol.)}$	$\theta_{15000(vol.)}$	AW
VDP_{FW}	−0.0573 [ns]	−0.0645 ns	−0.127 ns	−0.390 ns	0.271 ns
VDP_{SW}	−0.069 ns	0.570[*]	0.243 ns	0.242 ns	−0.002 ns
VDPR	0.084 ns	−0.270 ns	−0.186 ns	−0.539[**]	0.364 ns
$h_{modal-FW}$	0.406 ns	0.436 ns	0.026 ns	0.154 ns	−0.139 ns
$h_{modal-SW}$	0.085 ns	−0.255 ns	0.232 ns	−0.086 ns	0.317 ns
$h_{modal}R$	0.168 ns	0.183 ns	−0.110 ns	−0.111 ns	0.001 ns
SI_{FW}	−0.045 ns	−0.100 ns	−0.156 ns	−0.293 ns	0.146 ns
SI_{SW}	−0.075 ns	0.559[**]	0.210 ns	0.265 ns	−0.060 ns
SR	−0.118 ns	−0.292 ns	−0.021 ns	−0.335 ns	0.320 ns
S_iR	0.193 ns	−0.423 ns	−0.169 ns	−0.444[*]	0.284 ns

θ_{330} Water content at field capacity, θ_{15000} Water content at permanent wilting point, *AW* Available water, *VDP* Volume of drainable pores, h_{modal} Modal suction, *SI* Structural index, *SR* and S_iR Stability ratios calculated using the modified van Genuchten and van Genuchten models, respectively

ns, * and ** stand for non-significant and significant at 0.05 and 0.01 probability levels, respectively

Citrus : $\text{VDPR} = -0.120 + 2.95 \dfrac{\text{OM}}{\text{Clay}}$ $R^2 = 0.32**$

$$\tag{11}$$

Paddy field : $\text{VDPR} = -0.0121 + 3.008 \dfrac{\text{OM}}{\text{Clay}}$ $R^2 = 0.62**$

$$\tag{12}$$

The previous sections explained the relationship between soil organic matter and structural stability. The positive role of $\frac{\text{OM}}{\text{Clay}}$ ratio in these PTFs (Eqs. 10, 11, 12) indicates that soil OM irrespective of soil texture would increase the aggregate stability. It means that by increasing the $\frac{\text{OM}}{\text{Clay}}$ ratio, a higher amount of clay is complexed with OM, thus increasing the soil structural stability. Dexter et al. (2008) found that OM and clay particles have a significant effect on soil physical properties, including structural stability. Our findings are in accordance with the results of Hosseini et al. (2015, 2017), showing a strong correlation between soil structural stability indices and $\frac{\text{OM}}{\text{Clay}}$ ratio.

The following regression relation was derived to estimate the available water (AW) in the study area:

$$\text{AW} = -0.288 + 8 \times 10^{-6}(\text{CCE})^{3***} + 0.0075(\text{OM})^2 + 3.23\left(\frac{\text{N}}{\text{C}}\right)^{***} + 0.052(\rho_b)^3 \quad R^2 = 0.46^{***} \tag{13}$$

The positive effects of CCE (kg 100 kg^{-1}), OM (kg 100 kg^{-1}), N/C ratio (ratio of total nitrogen to organic carbon) and ρ_b (g cm^{-3}) on the AW (cm^3 cm^{-3}) were observed in this relationship. Whitbread et al. (1996) showed that the OC content of virgin soils decreased upon cultivation. The lower OC content can alter the pore size distribution and may reduce the soil water content especially in the wet range. Organic materials make the soil structure more stable, increase the size of the soil pores, and improve soil water retention (Whitbread et al. 1996). According to Wall and Heiskanen (2003), organic matter reduces the bulk density, porosity and increases soil water retention. Mosaddeghi and Mahboubi (2011) observed that there is a slight increase in soil water retention due to the effect of carbonate on aggregation. Asgarzadeh et al. (2014) showed that increasing the relative bulk density had a negative effect on the AW. A positive relationship between the AW and bulk density in the developed model (Eq. 13) can be due to the dominance of paddy soils in the studied soils and high AW in the paddy soils due to the presence of smectites (2:1 clay minerals).

Following regression relations were derived to estimate the gravimetric θ_{330} in the study area:

$$\theta_{330} = 0.24^{***} + 0.019\,\text{OM}^{**} \quad R^2 = 0.18^{**} \tag{14}$$

$$\theta_{330} = 0.081 + 0.032\,\text{OM}^{**} + 0.057\log(\text{CCE})$$
$$+ 0.0064\left(\frac{\text{OM}}{\text{Clay}}\right)^{-1*} \quad R^2 = 0.30^{**} \tag{15}$$

The positive effects of OM (kg 100 kg^{-1}), CCE (kg 100 kg^{-1}), and OM/Clay ratio on the θ_{330} (g g^{-1}) are observed in these relationships. Soil organic matter (OM) has important direct and indirect effects on AW which depend on factors such as soil texture and bulk density (Libohova et al. 2018). Organic materials would increase aggregation and thus affect the soil water availability for plant. In addition to better soil structure and greater porosity, organic matter can increase θ_{330} as well. Increasing the soil water content with increasing OM can be attributed to the high specific surface area and negative charges of organic materials, and its positive effect on soil structure formation. Analysis of Natural Resources Conservation Service (NRCS) database showed that by an increment of 1% in the OM content, the AW increased by 2% to > 5% depending on soil texture (Libohova et al. 2018). Mosaddeghi and Mahboubi (2011) found the dominant effect of OM on the soil water retention especially at low matric suction (e.g., at 330 hPa). Gupta and Larson (1979) reported that OM increases the soil water content at low matric suctions. With increasing the clay content, the soil water content is increased due to an increment in the frequency of micropores (i.e., textural pores) and specific surface area (greater adsorbed water).

Mosaddeghi and Mahboubi (2011) developed regression PTFs to estimate soil water content at different matric suctions in western Iran and reported that clay content had a significant and positive effect on soil water content (e.g., field capacity). In general, with increasing the clay content, the soil water content at a given matric suction increased. Similarly, Shirani and Rafienezhad (2011) observed that clay content had the most impact on the field capacity.

The following regression relation was derived to estimate the gravimetric wilting point (θ_{15000}) in the paddy fields as follows:

$$\theta_{15000} = 0.077^{***} + 0.0023\,\text{Clay}^{***} \quad R^2 = 0.34^{***} \tag{16}$$

where θ_{15000} is permanent wilting point (g g^{-1}) and Clay is clay content (kg 100 kg^{-1}). The PWP is mainly affected by the specific surface area of the soil particles, because in the dry range only very fine pores and adsorbed water play a role in the water retention. Among the mineral particles of soil, clay particles have the highest specific surface area. Ghorbani Dashtaki et al. (2011) also showed that the θ_{15000} had a

significant relationship only with the clay content, which is consistent with the results of this research. Similarly, these results are consistent with the findings of Shirani and Rafienezhad (2011) and Aina and Periaswamy (1985).

Conclusions

(1) Land use conversion led to a change in soil organic matter content. The highest soil organic matter was found in the forest land use, being significantly different from that of paddy field land use. In the citrus garden, the organic matter content was lower due to the low density of trees as well as their permanent greenery compared to the forest land use. In the paddy fields, although the organic matter was greater than other agricultural fields due to the dominant reducing conditions, it was lower than those in the forest and pasture land uses because burning straw after harvest reduced organic input into the soil.

(2) Land use had no significant effect on soil bulk density, but its highest value in the citrus garden can be attributed to poor structure and degradation of soil pore system due to high machinery traffic and farmers trampling during harvesting. Puddling has resulted in the highest bulk density in the paddy fields and an increase in the number of micropores. However, bulk density was low in pasture and forest land uses because of high organic matter and macropores.

(3) Land use had a significant effect on gravimetric content of field capacity. The highest field capacity was found in the forest land use due to higher organic matter, low bulk density and high porosity compared to other land uses. The field capacity and available water (AW) in the paddy fields, followed by forest land use, were higher than other land uses, which can be attributed to the presence of expandable smectitic clays in this land use. A decrease in field capacity and AW values in the citrus land use can be due to cultivation operations and accelerated decomposition of organic matter.

(4) Land use did not have a significant effect on soil structural stability as quantified by HEMC method, but there was a significant positive correlation between the volume of drainable pores ratio (VDPR) and ratio of organic matter content to clay content (OM/Clay ratio). Forest land use had the highest soil structural stability among the land uses. Soil structural stability in the paddy fields decreased due to reducing conditions and the presence of smectitic clays in comparison with other land uses. Furthermore, there was a significant positive correlation between AW and stability indices of VDP of fast-wetted samples (VDP_{FW}) and VDPR, which can be indirectly attributed to the effect of organic matter.

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