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Soil Atterberg Limits and Consistency Indices as Influenced by Land Use and Slope Position in Western Iran

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Abstract: Atterberg limits and consistency indices are used for classifications of cohesive (fine-grained) soils in relation with compaction and tillage practices. They also provide information for interpreting several soil mechanical and physical properties such as shear strength, compressibility, shrinkage and swelling potentials. Although, several studies have been conducted regarding the land use effects on various soil mechanical properties, little is known about the effects of land use and slope positions on Atterberg limits and consistency indices. This study was conducted to investigate the effects of land use and slope position on selected soil physical and chemical properties, Atterberg limits and consistency indices in hilly region of western Iran. Three land uses including dryland farming, irrigated farming and pasture and four slope positions (i.e., shoulder, backslope, footslope, and toeslope) were used for soil samplings. One hundred eleven soil samples were collected from the surface soil (0–10 cm). Selected physical and chemical properties, liquid limit (LL), plastic limit (PL) and shrinkage limit (SL) were measured using the standard methods; and consistency indices including plastic index (PI), friability index (FI), shrinkage index (SI) and soil activity (A=PI/clay) were calculated. The results showed that irrigated farming significantly increased organic matter content (OM) and OM/clay ratio, and decreased bulk density (ρ_b) and relative bulk density ($\rho_{b\text{-rel}}$) as a result of higher biomass production and plant residues added to the soil compared to other land uses. Except for sand content, OM, ρ_b, cation exchange capacity (CEC) and calcium carbonate equivalent (CCE), slope position significantly affected soil physical and chemical properties. The highest values of silt, OM/clay and CEC/clay were found in the toeslope position, predominantly induced by soil redistribution within the landscape. The use of complexed (COC) – non-complexed organic carbon (NCOC) concept indicated that majority of the studied soils were located below the saturation line and the OM in the soils was mainly in the COC form. The LL, PI, FI and A showed significant differences among the land uses; the highest values belonged to the irrigated farming due to high biomass production and plant residues returned to the soils. Furthermore, slope position significantly affected the Atterberg limits and consistency indices except for SL. The highest values of LL, PI, SI and A were observed in the toeslope position probably because of higher OM and CEC/clay due to greater amount of expandable phyllosilicate clays. Overall, soils on the toeslope under irrigated farming with high LL and SI and low values of FI need careful tillage management to avoid soil compaction.

Keywords: Land use; Slope position; Atterberg

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limits; Soil consistency; Relative bulk density; Complexed organic carbon

List of abbreviations, symbols and units

Parameter	Definition	Unit
LL	Liquid limit	kg 100kg^{-1}
PL	Plastic limit	kg 100kg^{-1}
SL	Shrinkage limit	kg 100kg^{-1}
PI	Plastic index	kg 100kg^{-1}
FI	Friability index	kg 100kg^{-1}
SI	Shrinkage index	kg 100kg^{-1}
A	Soil activity (i.e., ratio of plastic index to clay content=PI/clay)	–
OC	Organic carbon content	kg 100kg^{-1}
OM	Organic matter content	kg 100kg^{-1}
CCE	Calcium carbonate equivalent	kg 100kg^{-1}
CEC	Cation exchange capacity	cmol(+) kg^{-1}
ρ_b	Bulk density	Mg m^{-3}
$\rho_{b\text{-rel}}$	Relative bulk density	–
COC	Complexed organic carbon	kg 100kg^{-1}
NCOC	Non-complexed organic carbon	kg 100kg^{-1}
CC	Complexed clay	kg 100kg^{-1}
NCC	Non-complexed clay	kg 100kg^{-1}

Introduction

Physical and mechanical properties of cohesive (fine-grained) soils greatly depend on the water content. Soil consistency indicates the soil's resistance to deformation when exposed to mechanical forces. Based on gravimetric water content, Atterberg (1911) defined three consistency limits including shrinkage limit (SL), lower plastic limit or plastic limit (PL) and upper plastic limit or liquid limit (LL) for fine-grained soils. The SL is the limit between solid and semisolid states, PL is the border between semisolid and plastic states, and LL separates plastic state from liquid state (Casagrande 1932; Archer 1975; PCA 1992; Campbell 2001; Das 2006; McBride 2008). Soil consistency indices represent the water content ranges, over which specific mechanical behaviors occur. In the plastic range as quantified by plasticity index (i.e., PI=LL–PL), soil mechanical behavior is plastic/irreversible without cracking upon loading. In the semisolid state (between SL and PL), soil is friable and behaves in brittle manner (Campbell 2001; Das 2006; McBride 2008; Keller and Dexter 2012).

The Atterberg limits and consistency indices are used for classifications of cohesive (fine-grained) soils. They also provide information for interpreting several soil mechanical and physical properties such as shear strength, compressibility, shrinkage and swelling potentials (Archer 1975; Wroth and Wood 1978; Campbell 2001; McBride 2008; Seybold et al. 2008). These water content limits are also essential for infrastructure application (e.g., buildings and roads construction). Moreover, these limits and indices are helpful for classifying soils in relation with compaction and tillage practices (Soane et al. 1972; Campbell 2001), optimum water content for tillage (Campbell 2001; Dexter and Bird 2001; Keller et al. 2007; Mosaddeghi et al. 2009), and in soil-machine interactions (Campbell 2001).

The effects of soil intrinsic properties on the Atterberg limits and consistency indices have been commonly reported in the literature. de la Rosa (1979) found that clay content, cation exchange capacity (CEC) and organic matter (OM) had significant influences on PI variability in the Florida soils. de Jong et al. (1990) and Mbagwa and Abeh (1998) reported significant positive correlations between LL, PL and PI and clay content in southern Saskatchewan, Canada and tropical regions of Nigeria, respectively. Odell et al. (1960) showed that OM, clay content and the montmorillonite content in the clay fraction had significant influences on LL and PI. Seybold et al. (2008) indicated that clay content and CEC were highly related to LL and PI in a database in the US. Keller and Dexter (2012) also reported significant positive relationships of LL, PL and PI with clay content but not with OM using a soil database from different countries. Dexter et al. (2008) observed that, for mineral soils, it is not the total amount of organic carbon (OC) that controls soil physical and mechanical behavior, but the amount of complexed organic carbon (COC) or non-complexed OC (NCOC). They reported that for the soils where OC is mainly complexed (i.e., OC $\approx$ COC), inverse of bulk density (i.e., specific volume) is significantly related with the OC content, but not with the clay content. They assumed that this complex (COC) is formed by the association of unit mass (i.e., 1 g) of OC with 10 g of clay. Havaee et al. (2014) employed COC-NCOC concept of Dexter et al. (2008) for the soils under different land uses in Semirom region, central Iran. Their results showed that almost all of the soils located below the saturation line (1:10), indicating that the studied soils were not saturated with the OC and had all OC in the COC form. The irrigated soils were closer to the COC saturation line because of the higher organic material inputs in the irrigated farming.

There is extensive information around the world about the land use effects and to a lesser extent about the slope position effects on soil properties (e.g., Lal 2004; Celik 2005; Lorenz et al. 2008; Xie and Wei 2013; Falahatkar et al. 2014). The influences of land use changes and management practices have been studied on soil mechanical and physical attributes such as soil hydraulic properties (Green et al. 2003; Schwartz et al. 2003), soil strength (Blanco-Canqui et al. 2005; Havaee et al. 2015), sorptivity (Shaver et al. 2002), aggregate tensile strength (Arthur et al. 2012), degree of compactness (Havaee et al. 2014), and soil aggregation (e.g., Dexter and Horn 1988; Ayoubi et al. 2012). In Iran, few studies have been done on the effects of land use (change) (Ayoubi et al. 2011, Havaee et al. 2014, 2015; Kelishadi et al. 2014) and slope position (Khormali et al. 2009; Mokhatri Karchegani et al. 2011; Khormali and Ajami 2011) on soil quality indicators.

Although, several studies have been conducted regarding the land use effects on various soil mechanical properties, little is known about the effects of land use and slope positions on the Atterberg limits and consistency indices. Blanco-Canqui et al. (2006) investigated the effects of five land use managements including moldboard-plowed continuous corn, no-tilled continuous corn, no-till continuous corn with beef cattle manure application, and pasture and forest systems. They showed that no-till system had the lowest value of soil particle density and the highest values of OM, LL, PL and PI. Significant differences in the soil consistency limits were mainly attributed to the variation in OC values among the management systems.

Land use and slope position can indirectly affect the soil consistency limits and indices along the landscape. Presumably land use and slope positions by altering soil physical and chemical properties could regulate the soil consistency but documentation is scanty. This study was conducted to determine the possible influence of land use and slope position on selected soil physical and chemical properties, Atterberg limits and consistency indices in hilly region of western Iran.

1 Materials and Methods

1.1 Study area

This study was carried out on the hilly regions of Cherlgerd watershed located in western Iran (Figure 1). The study area is located between 50°5' to 50°28' E longitudes and 32°13' to 32°35' N latitudes and approximately covers an area of 370 km^2. The mean elevation of the study area is 2360 m a.s.l. The mean annual precipitation and temperature at the selected area are 1440 mm and 9.4°C, respectively (www.chaharmahalmet.ir).

The soils in the study area are developed mainly on Cretaceous limestone and Oligo-Miocene deposits and classified as Entisols, Inceptisols and Vertisols (Mehnatkesh et al. 2013) after Soil Survey Staff (2010). Major land uses include pasture, dominantly covered by milkvetch (*Astragalus* sp.) and brome grasses (*Bromus* sp.), and dryland farming and irrigated farming mainly consisting of winter wheat (*Triticum aestivum*) and alfalfa (*Medicago sativa*), respectively (Kelishadi et al. 2014).

1.2 Soil sampling and analyses

Soil surface layer (0–10 cm) was sampled at 111 locations in September, 2012. Surface soil was sampled because its mechanical behavior is important in soil erosion processes/modelling and tillage studies and much difference among the soil properties such as texture, CCE and OM is expected to occur in the surface soil. Sampling points had a good scatter representing the study region, considering soil variability, different land uses and slope position (Figure 1). Three major land uses and four slope positions were considered for soil sampling in the region. Numbers of sampling locations were 34, 23 and 54 for dryland farming, irrigated farming and pasture land uses, respectively, depending on the area covered by each land use. Numbers of the sampling points among the slope positions were 18, 20, 42 and 31

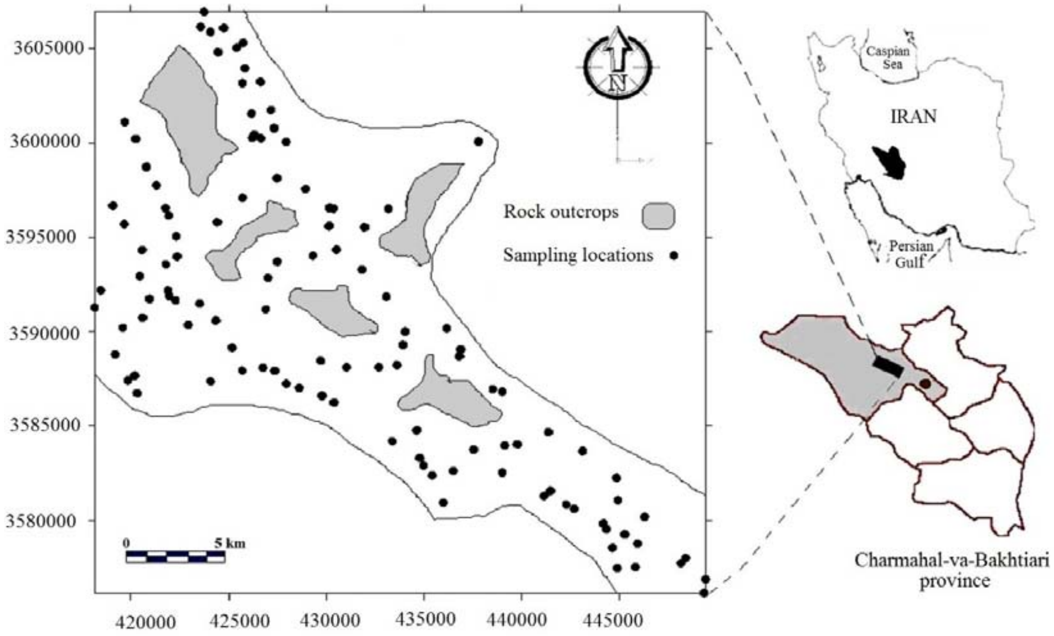

Figure 1 Location of the study region in west of Iran and spatial distribution of soil sampling sites in the region.

for shoulder, backslope, footslope and toeslope, respectively. In order to reduce micro-variability, in each location three soil samples were collected and mixed, and the composite samples were brought to the laboratory. An undisturbed soil sample was also collected from the surface soil using Kopecky core samplers of 4.9 cm diameter and 5.3 cm height (i.e., 100 cm^3) to measure bulk density (ρ_b) by oven-drying at 105°C for 48 h.

Soil samples were air-dried and passed through 2-mm sieve for laboratory analyses. Soil texture and particle size distribution (clay, silt and sand fractions, PSD) were measured using the pipette method (Gee and Bauder 1986). Soil organic matter (OM) was determined using the Walkley-Black method (Nelson and Sommers 1982). Calcium carbonate equivalent (CCE) was measured by the Bernard's calcimetric method (Richard and Suarez 1996). Cation exchange capacity (CEC) was measured using the sodium acetate method (Rhoades 1982).

The liquid limit (LL), plastic limit (PL) and shrinkage limit (SL) were determined on soil material passing a 0.425-mm sieve according to the standard methods. The LL was determined using the Casagrande *three-point* method. Soil sample was wetted with distilled water, remolded and put in the cup of Casagrande apparatus. The sample was divided in two by drawing grooving tool through the sample. The cup was alternatively raised 10-mm above the base by a crank and dropped freely onto the base at two revolutions per second until the two parts of the soil came into contact at the bottom of the groove over a length of 13-mm. The number of blows required to do this was recorded. Then, more distilled water was added to the soil sample and the procedure was repeated for another two water contents to give a range of results lying between 50 and 10 blows. The linear relation between the water contents and the log of the numbers of blows was plotted, and the gravimetric water content corresponding to 25 blows was recorded as the LL (Casagrande 1932; BSI 2000; Campbell 2001). The PL was measured using the 3-mm soil thread method, as the water content at which a 3-mm remolded soil thread begins to crack longitudinally and transversely (Casagrande 1932; BSI 2000; Campbell 2001; McBride 2008). The SL was determined by the linear shrinkage method (BSI 2000). Gravimetric water contents at the Atterberg limits were measured by oven-drying the soil at 105°C for 48 h.

The plastic/plasticity index (PI=LL–PL), friability index (FI=PL–SL) and shrinkage index (SI=LL–SL) as soil consistency indices were calculated (BSI 2000; Campbell 2001; McBride 2008). The ratio of PI to clay percent (i.e., PI/clay) was also considered as soil activity (*A*), indicating the physical and mechanical activity of the clay fraction. The *A* mostly depends on the dominant clay minerals, exchangeable cations and salts in the soil solution (Campbell 2001).

In order to evaluate the degree of compactness irrespective of soil type (i.e., clay content), the relative bulk density ($\rho_{\text{b-rel}}$) as the ratio of ρ_{b} to a reference ρ_{b} ($\rho_{\text{b-ref}}$) was calculated as follows:

$$\rho_{\text{b-rel}} = \frac{\rho_{\text{b}}}{\rho_{\text{b-ref}}} \tag{1}$$

where $\rho_{\text{b-ref}}$ was calculated as a function of clay content by following equation (Jones 1983; Dexter 2004):

$\rho_{\text{b-ref}}$ (Mg m^{-3}) = 1.882 – 0.0083Clay (kg $100kg^{-1}$) (2)

Mosaddeghi et al. (2009) observed that $\rho_{\text{b-ref}}$ calculated using Eq. 2 has a strong correlation with natural soil ρ_{b}. The $\rho_{\text{b-rel}}$ might be better linked to several physical soil functions such as water and air storage, mechanical impedance to root growth, and water availability for plants when compared to ρ_{b} (e.g., see Asgarzadeh et al. 2010, 2011). The ρ_{b} and $\rho_{\text{b-rel}}$ were used to assess the impact of land use and slope position on degree of compactness of the soils in the region.

1.3 Statistical analyses

Descriptive statistics including minimum, maximum, mean, and standard deviation (SD) were computed using SPSS v. 17.0 (IBM Com., Chicago, USA). Coefficient of variation (CV) was employed for exploring the variability of the selected parameters and properties in the study area. Analysis of variance (ANOVA) was done in a completely randomized design with unequal replications. Since all of the land uses were not found in all of the slope positions, one-way ANOVA was done separately for three land uses including irrigated farming, dryland farming and pasture and four slope positions comprising of shoulder, backslope, footslope and toeslope. Therefore, it was not possible to investigate the interactive effects of land use and slope position on the Atterberg limits and consistency indices. The data were analyzed using ANOVA in the SPSS v. 17.0. Means' comparison was done using the Duncan's multiple range method at $p<0.05$ probability level.

We used the COC-NCOC concept proposed by Dexter et al. (2008) to discriminate the organic matter status of the studied soils under different land uses and on different slope positions. We also followed the concept of complexed clay (CC) and non-complexed clay (NCC) described by Dexter et al. (2008) and Dexter and Czyż (2011), to evaluate the effects of land use and slope position on the clay fractions. Correlation analysis was also done in the SPSS v. 17.0.

2 Results and Discussion

2.1 Soil physical and chemical properties

A summary of statistics for the soil physical and chemical properties categorized based on the land use are given in Table 1. The most variable property in the three land uses was CCE with CV values of 72.2, 69.7 and 77.2 kg $100kg^{-1}$, for dryland farming, irrigated farming and pasture, respectively. Sand content also showed high variability in the land uses following CCE. However, ρ_{b} and $\rho_{\text{b-rel}}$ had the lowest variability among the land uses in the study area. No significant difference was found between land uses in terms of the mean values of primary particle-size fractions and CCE (Table 1), presumably because these intrinsic soil properties are mainly influenced by parent material and geomorphic positions rather than management practices.

The organic matter content (OM) was highly variable in all of the studied land uses; on an average, irrigated farming had the highest and dryland farming together with pasture showed the lowest mean OM (i.e., 1.34 kg $100kg^{-1}$, see Table 1). The differences in OM means between land uses were significant in the order: irrigated farming > dryland farming = pasture (Table 1). The highest means of OM and OM/clay ratio and the lowest means of ρ_{b} and $\rho_{\text{b-rel}}$ were obtained for the irrigated farming due to organic manure application, higher crop production and greater plant residues returned to the soil. Similar results were reported by Havaee et al. (2014) in Semirum district in central Iran. Pasture and dryland farming showed similar low values of OM, ρ_{b} and $\rho_{\text{b-rel}}$. Lower values of OM in the pasture and dryland farming might be attributed to intensive grazing and sparse vegetation in the pasture, and little addition of litters and residues to the soil plus intensive tillage practices in the dryland farming

Table 1 **Descriptive statistics and means' comparisons of soil physical and chemical properties among different land uses (LU) in the study region**

LU	Variable	Min	Max	Mean*	CV (%)	SD
Dryland farming (*N*=34)	Clay (kg 100kg^{-1})	6.4	58.4	34.2^{a}	33.9	11.6
	Silt (kg 100kg^{-1})	39.4	83.8	58.2^{a}	19.4	11.3
	Sand (kg 100kg^{-1})	2.0	19.2	7.6^{a}	63.2	4.8
	OM (kg 100kg^{-1})	0.38	2.79	1.34^{b}	46.3	0.62
	CCE (kg 100kg^{-1})	1.5	50.0	16.9^{a}	72.2	12.2
	CEC (cmol(+) kg^{-1})	24.5	69.5	51.5^{a}	18.3	9.4
	CEC/clay	0.90	5.05	1.76^{a}	53.4	0.94
	ρ_b (Mg m^{-3})	1.10	1.48	1.24^{a}	8.1	0.10
	$\rho_{b\text{-rel}}$	0.60	0.99	0.78^{ab}	8.9	0.07
	OM/clay	0.01	0.23	0.05^{b}	100.0	0.05
Irrigated farming (*N*=23)	Clay (kg 100kg^{-1})	4.0	56.0	30.3^{a}	43.9	13.3
	Silt (kg 100kg^{-1})	41.00	86.4	61.6^{a}	21.3	13.1
	Sand (kg 100kg^{-1})	2.0	15.7	8.1^{a}	51.9	4.2
	OM (kg 100kg^{-1})	0.46	4.38	2.07^{a}	54.1	1.12
	CCE (kg 100kg^{-1})	0.0	55.0	21.8^{a}	69.7	15.2
	CEC (cmol(+) kg^{-1})	2.5	57.0	42.2^{b}	30.1	12.7
	CEC/clay	0.07	9.37	2.12^{a}	101.9	2.16
	ρ_b (Mg m^{-3})	1.09	1.37	1.21^{a}	6.6	0.08
	$\rho_{b\text{-rel}}$	0.61	0.87	0.74^{b}	9.5	0.07
	OM/clay	0.01	0.60	0.12^{a}	116	0.14
Pasture (*N*=54)	Clay (kg 100kg^{-1})	3.2	49.7	35.7^{a}	26.1	9.3
	Silt (kg 100kg^{-1})	42.6	85.8	57.6^{a}	16.3	9.4
	Sand (kg 100kg^{-1})	1.0	18.1	6.7^{a}	67.2	4.5
	OM (kg 100kg^{-1})	0.1	3.38	1.34^{b}	44.0	0.59
	CCE (kg 100kg^{-1})	1.0	45.3	16.2^{a}	77.2	12.5
	CEC (cmol(+) kg^{-1})	27.1	70.3	49.7^{a}	18.1	9.0
	CEC/clay	0.70	10.57	1.66^{a}	88.6	1.47
	ρ_b (Mg m^{-3})	1.07	1.50	1.25^{a}	7.2	0.09
	$\rho_{b\text{-rel}}$	0.60	0.99	0.79^{a}	8.9	0.07
	OM/clay	0.001	0.6	0.05^{b}	160	0.08

Notes: OM, Organic matter; CCE, Calcium carbonate equivalent; CEC, Cation exchange capacity; ρ_b, Bulk density; $\rho_{b\text{-rel}}$, Relative bulk density; Minimum; Max, Maximum; CV, Coefficient of variation; SD, Standard deviation.

* For each property, the values with different letters among the land uses are significantly different (Duncan's test, $p<0.05$).

(Kelishadi et al. 2014). The differences in $\rho_{b\text{-rel}}$ means among the land uses could be elucidated by the influences of OM on ρ_b. The decreasing impact of OM on the degree of compactness might be due to dilution effect (i.e., low density of the organic materials) and because OM improves soil aggregation and hence increases soil porosity (Mosaddeghi et al. 2000; Havaee et al. 2014, 2015).

The results of ANOVA showed that the slope position significantly affected the soil physical and chemical properties except for sand content, OM, ρ_b, CEC and CCE (Table 2). Along the landscape, soils located in the toeslope position had significantly higher silt content (i.e., 66.7 kg 100kg^{-1}) when compared to the other slope positions (Table 3). This may be due to susceptibility of the silt fraction to erosion and preferential movement of those particles from the upper slopes to toeslope position (Rhoton et al. 2002; Khormali et al. 2009; Mokhtari Karchegani et al. 2011). The OM/clay and CEC/clay ratios were higher in the lower positions compared to the upper ones. Higher values of CEC/clay ratio in the toeslope position are mainly attributed to greater 2:1 expandable clays (i.e., smectites) in this position (Zolfaghari 2014), which increased the clay activity.

In contrast to some other results reported from Iran (Khormali et al. 2009; Ayoubi et al. 2012; Karchegani et al. 2012), slope position did not significantly affect sand, OM, ρ_b, CEC and CCE in our study. It seems that high diversity in the land uses and management practices on different geomorphic positions could mask the distinguishable effect of slope position on some soil properties.

2.2 Complexed and non-complexed organic carbons and clays

Dexter et al. (2008) and Dexter and Czyż (2011) confirmed that in mineral soils using the concept of complexed organic carbon (COC) and non-complexed organic carbon (NCOC) better explains soil physical behavior compared to the total OC. We employed COC-NCOC concept of Dexter et al. (2008) and calculated COC and NCOC for our samples. The results showed that majority of the studied soils were located below the saturation line (1:10) and the OC in the soils was dominantly in the COC form (Figures 2a and 2b). However, four out of 23 soils (17%) in irrigated farming, three out of 54 soils (5.5%) in pasture, and

Table 2 The analysis of variance (ANOVA) for land use and slope position effects on soil physical and chemical properties in the study region

Statistics	Clay	Silt	Sand	OM	CCE	CEC	ρ_b	$\rho_{b\text{-rel}}$
Land use effect								
Mean square	233.86	134.83	17.54	4.84	268.48	648.11	0.008	0.012
F value	1.95	1.15	0.86	8.76	1.59	6.5	0.86	3.27
Significance level	0.147	0.32	0.425	0.0001	0.209	0.002	0.425	0.049
Slope position effect								
Mean square	1036.61	1031.65	15.14	0.81	41.18	158.14	0.01	0.03
F value	10.76	11.24	0.74	1.29	0.23	1.46	1.30	7.11
Significance level	0.0001	0.0001	0.529	0.279	0.871	0.229	0.275	0.0001

Notes: OM, Organic matter; CCE, Calcium carbonate equivalent; CEC, Cation exchange capacity; ρ_b, Bulk density; $\rho_{b\text{-rel}}$, Relative bulk density.

Table 3 Effects of slope position on soil physical and chemical properties among different slope positions in the study region*

Slope position	Clay (kg 100kg^{-1})	Silt (kg 100kg^{-1})	Sand (kg 100kg^{-1})	OM (kg 100kg^{-1})	CCE (kg 100kg^{-1})	CEC (cmol(+) kg^{-1})
Shoulder (N=18)	36.7^{a} (±10.9)	55.0^{b} (±9.6)	8.3^{a} (±4.9)	1.35^{a} (±0.58)	18.3^{a} (±12.9)	47.7^{a} (±5.8)
Backslope (N=20)	41.1^{a} (±6.7)	52.7^{b} (±4.7)	6.2^{a} (±4.4)	1.25^{a} (±0.65)	17.7^{a} (±13.9)	49.9^{a} (±10.1)
Footslope (N=42)	35.5^{a} (±8.1)	56.9^{b} (±8.8)	7.5^{a} (±4.7)	1.56^{a} (±0.75)	16.3^{a} (±12.4)	50.7^{a} (±8.9)
Toeslope (N=31)	26.2^{b} (±12.5)	66.7^{a} (±12.4)	7.0^{a} (±3.9)	1.64^{a} (±0.99)	18.8^{a} (±12.7)	45.8^{a} (±13.8)

Slope position	ρ_b (Mg m^{-3})	$\rho_{b\text{-rel}}$	OM/clay	CEC/clay	CC (kg 100kg^{-1})	NCC (kg 100kg^{-1})
Shoulder (N=18)	1.25^{a} (±0.09)	0.79^{ab} (±0.07)	0.07^{ab} (±0.03)	1.81^{ab} (±0.52)	7.4^{a} (±3.5)	29.3^{ab} (±10.5)
Backslope (N=20)	1.27^{a} (±0.10)	0.82^{a} (±0.07)	0.03^{b} (±0.01)	1.23^{b} (±0.06)	7.2^{a} (±3.9)	34.0^{a} (±6.8)
Footslope (N=42)	1.23^{a} (±0.10)	0.77^{bc} (±0.07)	0.05^{b} (±0.02)	1.52^{b} (±0.08)	9.0^{a} (±4.3)	26.5^{b} (±8.6)
Toeslope (N=31)	1.22^{a} (±0.08)	0.73^{c} (±0.06)	0.11^{a} (±0.08)	2.49^{a} (±0.35)	8.1^{a} (±4.2)	18.1^{c} (±13.1)

Notes: OM, Organic matter; CCE, Calcium carbonate equivalent; CEC, Cation exchange capacity; ρ_b, Bulk density; $\rho_{b\text{-rel}}$, Relative bulk density; CC, Complexed clay content; NCC, Non-complexed clay content. The values in parentheses are standard deviations.

* In each column, values with different letters are significantly different (Duncan's test, $p<0.05$).

two out of 34 soils (5.9%) in dryland farming fell above the saturation line and were saturated with organic carbon (i.e., had values of OC > clay/10) (Figure 2a).

This indicates that irrigated soils are relatively in better condition in terms of organic matter in the region. However, the findings of Soussan et al. (2004) implied that in pasture soils, COC could be persevered for longer time if not disturbed. Thus non-complexed/non-protected OC is sensitive to soil management practices as it is vulnerable to decomposition (Dexter et al. 2008). In addition, the COC-NCOC concept of Dexter et al. (2008) was applied for the soil samples on various slope positions (Figure 2b). Almost all of the samples positioned below the saturation line (1:10), whereas some soil samples from toeslope position were located above the saturation line (Figure 2b). This finding might be due to the fact that majority of irrigated soils are located on the toeslope position.

The concept of complexed clay (CC) and non-complexed clay (NCC) described by Dexter et al. (2008) and Dexter and Czyż (2011) was also used to evaluate the effect of land use on the clay fractions. The means' comparison of total clay showed no significant difference between the land uses (Figure 3), but CC and NCC interestingly showed significant differences among them. The greatest mean of CC (i.e., 10.4 kg 100kg^{-1}) was observed in the irrigated farming, whereas the smallest values (i.e., 7.5 kg 100kg^{-1}) were obtained in the dryland farming and pasture. However, the greatest value of NCC was calculated for the dryland farming and pasture (Figure 3). Dexter et al. (2008) using the POLSTAB database, demonstrated that NCC was more readily dispersed in the water than CC. Therefore, it might be implied that clay particles are less water-dispersible in the irrigated soils compared to the soils under dryland and pasture in our study.

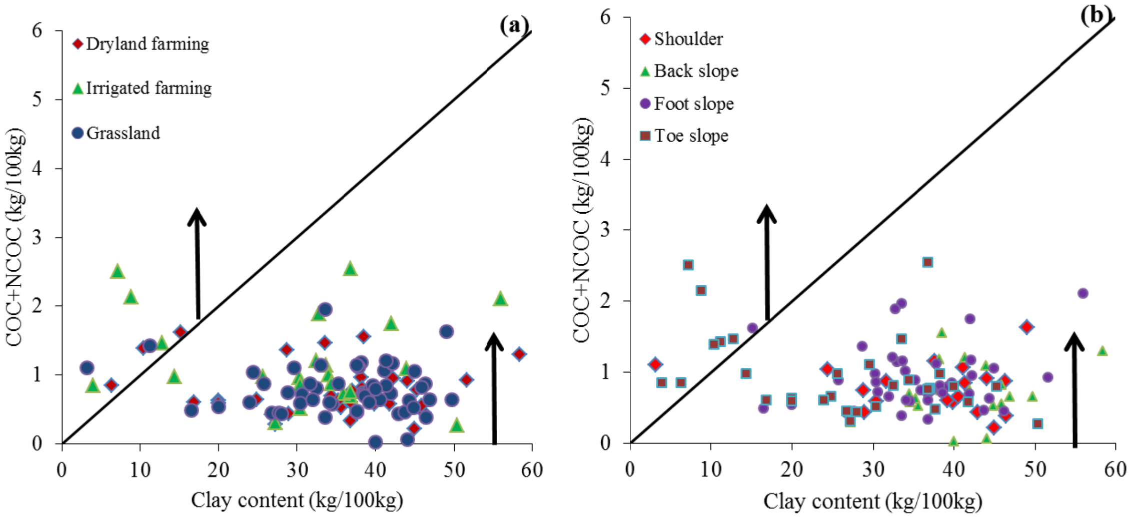

Figure 2 Application of COC-NCOC concept proposed by Dexter et al. (2008) for the studied soils as categorized by (a) land use and (b) slope position. The diagonal line is saturation line (1:10 line). The points below the line refer to the contents of complexed organic carbon (COC) and heights above the 1:10 line are contents of non-complexed organic carbon (NCOC).

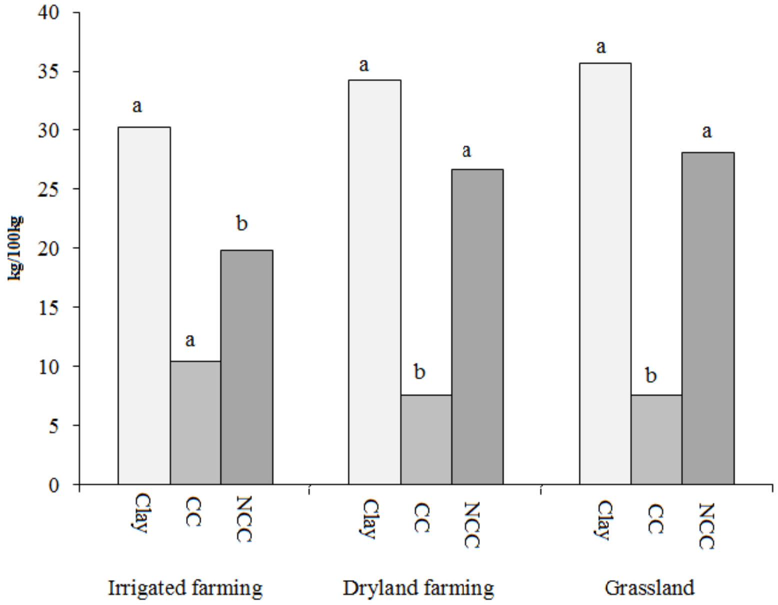

Figure 3 Means' comparisons of total clay, complexed clay (CC) and non-complexed clay (NCC) among the studied land uses. The bars corresponding to each clay fraction with different letters are significantly different (Duncan's test, $p<0.05$).

No significant differences were found for the sand and complexed clay (CC) contents among the slope positions, whereas significant differences were observed for the total clay and NCC. The lowest and highest means of total clay and NCC were found in the toeslope and backslope, respectively (Table 3).

2.3 Atterberg limits and consistency indices

Descriptive statistics of the results on the Atterberg limits and consistency indices and soil activity (A) in different land uses are presented in Table 4. The most variable quantity among the land uses was A with CV values of 76.0%, 88.7% and

46.9% for dryland farming, irrigated farming and pasture, respectively. Following *A*, PI and FI were most variable in the three land uses. However, LL showed the least variability with CV values of 13.6%, 13.8% and 10.7% in dryland farming, irrigated farming and pasture, respectively. Among the Atterberg limits and consistency indices, LL, PI and SI showed significant (p<0.05) differences between the land uses and the highest values were obtained for the irrigated farming (Table 4). The highest mean value of LL (i.e., 53.8 kg 100kg^{-1}) was observed for the irrigated farming, and showed no significant difference with its mean value in the dryland farming (i.e., 50.8 kg 100kg^{-1}), but significantly differed from that in the pasture.

Table 4 Descriptive statistics and means' comparisons of Atterberg limits and consistency indices among different land uses in the study region

Land use	Variable (kg 100kg^{-1})	Min	Max	Mean*	CV (%)	SD
Dryland farming (N=34)	LL	36.7	77.6	50.8^{ab}	13.6	6.9
	PL	5.7	42.7	30.2^{a}	25.4	7.7
	SL	8.5	16.2	12.0^{a}	16.7	2.0
	PI	5.3	48.0	20.6^{ab}	45.6	9.4
	FI	2.1	32.3	18.2^{a}	41.8	7.6
	SI	27.1	66.3	38.8^{ab}	16.0	6.2
	A (–)	0.18	2.67	0.71^{b}	76.0	0.54
Irrigated farming (N=23)	LL	39.1	67.0	53.8^{a}	13.8	7.4
	PL	10.5	47.5	29.3^{a}	29.0	8.5
	SL	9.7	15.7	12.9^{a}	13.9	1.8
	PI	10.2	46.9	24.4^{a}	36.5	8.9
	FI	2.3	33.21	16.4^{a}	48.1	7.9
	SI	26.0	57.4	40.9^{a}	17.6	7.2
	A (–)	0.33	4.20	1.15^{a}	88.7	1.02
Pasture (N=54)	LL	40.3	62.1	49.5^{b}	10.7	5.3
	PL	3.5	49.1	32.7^{a}	25.1	8.2
	SL	8.4	15.8	12.5^{a}	13.6	1.7
	PI	0.8	42.3	16.8^{b}	43.5	7.3
	FI	4.9	35.9	20.2^{a}	36.6	7.4
	SI	29.2	49.7	37.1^{b}	11.9	4.4
	A (–)	0.10	1.30	0.49^{b}	46.9	0.23

Notes: LL, Liquid limit; PL, Plastic limit; SL, Shrinkage limit; PI, Plastic index; FI, Friability index; SI, Shrinkage index; *A*, Activity (=PI/clay); CV, Coefficient of variation; SD, Standard deviation.
*For each property, the values with different letters among the land uses are significantly different (Duncan's test, p<0.05).

As already reported by other researchers (Odell et al. 1960; de la Rosa 1979; Seybold et al. 2008), clay content and type, and OM content were found to be the most important factors affecting LL. There was no significant difference among the land uses in terms of particle size distribution and clay content (Table 1); therefore, the dissimilarity in LL values among the land uses might be associated with the variation in OM content. The highest mean of OM was observed in the irrigated farming (Table 1) corresponding to the highest mean of LL (Table 4). Hemmat et al. (2010) and Keller and Dexter (2012) reported positive significant correlations of LL with OM when soil type (texture) was similar.

It has been reported that clay content has a predominant role in explaining the variability of the Atterberg limits. Several researchers (Odell et al. 1960; de Jong et al. 1990; Keller and Dexter 2012) reported strong positive correlations between the clay content and the Atterberg limits. However, Zolfaghari (2014) reported no significant correlations between the clay content and the Atterberg limits for the dataset used. In the present study, we used the CC-NCC concept of Dexter et al. (2008) to evaluate the effects of CC and NCC on the Atterberg limits in various land uses. Among the Atterberg limits and consistency indices, only LL and SI showed better correlations with the clay content when the CC-NCC concept was applied, while for PL and other consistency indices (i.e., PI and FI), no improvement in the correlations was observed. Similarly, the clay content did not show significant correlation with LL (r=0.04) in the dryland farming; but when CC was employed, significant correlation (r=0.34, p<0.01) was obtained between LL and CC. In the irrigated farming, greater improvement was achieved when correlation between CC and LL was calculated (r=0.39, p<0.01) rather than when correlation between clay content and LL was determined (r=–0.11, p<0.05). However, there was no

Table 5 **The analysis of variance (ANOVA) for land use and slope position effects on Atterberg limits and consistency indices in the study region**

Statistics	LL	PL	SL	PI	FI	SI
Land use effect						
Mean square	144.71	119.33	5.205	496.73	128.24	120.83
F value	3.68	1.81	1.51	7.14	2.23	3.83
Significance level	0.028	0.168	0.226	0.001	0.112	0.025
Slope position effect						
Mean square	206.59	493.36	3.24	1225.66	550.43	160.88
F value	5.65	8.99	0.93	27.17	12.24	5.43
Significance level	0.001	0.0001	0.43	0.0001	0.0001	0.002

Notes: LL, Liquid limit; PL, Plastic limit; SL, Shrinkage limit; PI, Plastic index; FI, Friability index; SI, Shrinkage index.

improvement in the relationship between clay content and LL based on the CC-NCC concept in the pasture (*r*=0.14 for both). Similar trends were observed for the SI (i.e., increase in correlation coefficients from 0.19 to 0.38; from –0.06 to 0.49; and from 0.15 to 0.22 between SI with clay and CC, for the dryland farming, irrigated farming and pasture, respectively). It seems that the quality of organic matter and presumably type of clay minerals which produce complexes with the OM in different land uses led to variable formation of clay complexes and hence variable effects on the Atterberg limits. Accordingly, Dexter et al. (2008) suggested that soil physical behavior is not controlled by OM, but by the amount of OM which is complexed with the clay particles.

With regard to *A* (PI/clay), significant differences were observed among the land uses (Table 4). The highest and lowest values of *A* were observed in the irrigated farming (i.e., 1.15) and dryland farming (i.e., 0.49), respectively. These findings might be attributed to higher contents of expandable 2:1 clay minerals (i.e., smectites) in the irrigated soils which are mostly located on the lower slope positions in the landscape (Zolfaghari 2014).

The results of ANOVA showed that slope position had significant influence on all of the Atterberg limits and consistency indices, except for SL (Table 5). The means' comparisons using Duncan's test (p<0.05) are given in Figure 4. The highest values of LL, PI, and SI (i.e., 54.5, 27.2 and 41.6 kg 100kg^{-1}, respectively) were observed on the toeslope position. The lowest values were obtained for the shoulder position with mean values of 48.3, 9.8 and 36.1 kg 100kg^{-1}, respectively (Figure 4). Comparing these results with the trends of soil properties in various slope positions (Table 3) confirmed that these differences might be partly related to the OM differences among the slope positions. The highest OM content was observed in the toeslope position, which showed the highest values of LL, PI, SI and *A*. The differences in the Atterberg limits and consistency indices among the

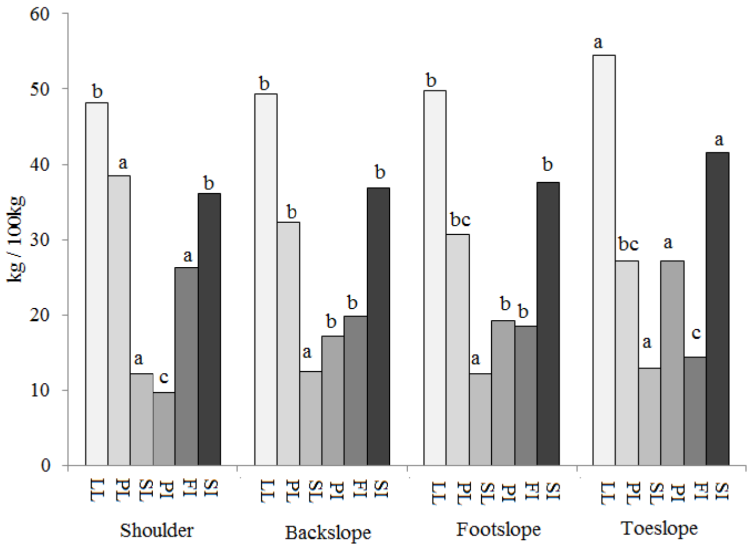

Figure 4 Means' comparisons of Atterberg limits and consistency indices among the slope positions. The bars corresponding to each limit/index with different letters are significantly different (Duncan's test, p<0.05).

slope positions are not directly attributable to the clay content variation because the lowest clay content was observed in the toeslope position (Table 3). As the relations between soil consistency limits and clay content were weak, the influence might be ascribed to the fractions coarser than the clay fraction or to the existence of aggregated clay-sized particles as reported by Coleman et al. (1964) and Campbell (2001). Moreover, a part of this discrepancy on the relationships between the clay content, slope position and above-mentioned Atterberg limits and consistency indices (i.e., PI, SI and *A*) might be related to the clay type.

Zolfaghari (2014) showed that the dominant clay minerals in the lower positions (toeslope) are expandable clay minerals such montmorillonite; and in the upper slopes they are non-active phyllosilicates such as chlorites and micas. The highest value of CEC/clay in the toeslope position (CEC/clay=2.49, Table 3) supports these findings. Odell et al. (1960) also showed that montmorillonite percent strongly correlated with the LL, PL and PI. It seems that soil redistribution within the studied landscapes and transposition of fine clay from upslopes to down slopes led to an increase in the expandable 2:1 clays in the lower positions. Khormali and Ajami (2011) in northern Iran and Mokhtari Karchegani et al. (2011) in western Iran reported higher accumulation of smectites as a result of soil redistribution in the lower slope positions of hilly landscapes.

Otherwise, the highest values of PL and FI were observed in the shoulder position (Figure 4), which might be due to significant higher clay content in this slope position (41.1 kg 100kg^{-1}) as compared to the other ones (Table 3). Hathaway-Jenkins et al. (2011) studying land use effects on the Atterberg limits, reported higher PL under conventionally managed grasslands than under conventional arable farming because of higher clay content.

3 Conclusions

(1) Land use significantly affected several soil properties and the irrigated farming increased OM, OM/clay ratio, and decreased ρ_b and $\rho_{b\text{-rel}}$ compared to other land uses. This finding is probably attributable to high biomass production and addition of plant residues to the soil in the irrigated farming.

(2) Slope position significantly affected soil physical and chemical properties except for sand content, OM, ρ_b, CEC and CCE; and the highest values of silt, OM/clay and CEC/clay were found in the toeslope position, mainly due to soil redistribution within the landscape.

(3) The use of COC-NCOC concept proposed by Dexter et al. (2008) showed that majority of the studied soils were located below the saturation line (i.e., were not saturated with organic carbon) and the OC in the soils was in the complexed (COC) form. The use of CC-NCC concept proposed by Dexter et al. (2008) showed that while the total clay was not significantly different, the CC and NCC significantly differed among the land uses. The CC-NCC clay fractions in different land uses showed higher correlation coefficients as compared to total clay with LL and SI in the irrigated and dryland farming systems. However, no significant improvement in the correlations with the Atterberg limits and consistency indices was observed by using CC instead of total clay under the pasture.

(4) The Atterberg consistency limits and indices were significantly different among the land uses and slope positions. The LL, PI, FI and *A* showed significant differences among the land uses and the highest values were obtained for the irrigated farming due to high biomass production and addition of plant residues to the soil. Except for SL, slope position significantly affected the Atterberg limits and consistency indices. The highest values of LL, PI, SI and *A* were observed in the toeslope position probably because of higher OM and CEC/clay (i.e., greater content of expandable phyllosilicate clays). Therefore, soils on the toeslope under irrigated farming with high LL and SI and low values of FI need careful tillage management to avoid soil compaction.

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