Soil & Tillage Research 181 (2018) 152–159

Contents lists available at ScienceDirect

Soil & Tillage Research

journal homepage: www.elsevier.com/locate/still

Effects of biological soil crusts on some physicochemical characteristics of rangeland soils of Alagol, Turkmen Sahra, NE Iran

Jalil Kakeh[a], Manouchehr Gorji[a,*], Mohammad Sohrabi[b], Ali Tavili[c], Ahmad Ali Pourbabaee[a]

[a] Soil Sciences Department, University of Tehran, Iran
[b] Biotechnology Department, Iranian Research Organization for Science and Technology, Iran
[c] Department of reclamation of arid and mountainous regions, University of Tehran, Iran

ARTICLE INFO

Keywords:
Alagol rangelands
Biocrusts
Lichens
Infiltration
Salinity
Turkmen Sahra

ABSTRACT

Salinity, water scarcity in the summer season, and grazing pressure are major problems in semi-arid ecosystems in the south-east region of the Caspian Sea where the Alagol rangelands of Turkmen Sahra (Golestan province) of North East Iran suffer from over-grazing and soil loss. This study investigated the influence of biological soil crusts (biocrusts) on soil physicochemical properties. Biocrusts create complex communities of specialized organisms composed of cyanobacteria, algae, microfungi, lichens, mosses and other microorganisms. Results have shown that bioencrusted soils increased levels of organic carbon, nitrogen, phosphorus, copper, and iron, and reduced pH, calcium carbonate, sodium, calcium, magnesium, sodium adsorption ratio and exchangeable sodium percentages compared to soils without biocrusts. Other positive influences of biocrusts on soil properties included increased infiltration (0.16 *v.* 0.081 cm min^{-1} for steady state rates), available water content, mean weight diameter of soil aggregates, geometric mean diameter and water stable aggregates. Bulk density was reduced under bioencrusted soils relative to non-biocrusts soils. In general, biocrusts had a positive effect on many soil properties and thus enhanced soil quality.

1. Introduction

Soil crusts are a major structural feature of surface soils and sediments, especially in arid and semi-arid regions (Fang et al., 2007). Soil crusts are divided into several types, including physical, chemical and biological soil crusts (Belnap et al., 2003a). Physical and biological soil crusts are the principal types of soil crusts (Miralles-Mellado et al., 2011), and are distributed in arid, semi-arid and sub-humid regions that constitute over 40% of the Earth's terrestrial surface (Belnap, 2006; Fang et al., 2007). Biological soil crusts (biocrusts) result from an intimate association between soil particles and cyanobacteria, algae, fungi, lichens and mosses which live on the surface or in the uppermost few millimeters of soils (Belnap et al., 2003a). These organisms and the extracellular polysaccharide materials associated with them connect soil particles together, creating a sticky living crust that covers the surface of many dry land regions in the worldwide (Belnap, 2006). Biocrusts occur on all major soil types and in almost all vegetative communities where sunlight can reach the soil surface (Belnap, 2006); they have low moisture requirements and a high tolerance of extreme temperatures and high ultraviolet (UV) light flux, thus enabling them to survive under conditions that can limit vascular plant growth (Belnap et al., 2003a). The species composition and external morphology of biocrusts vary according to the climatic regime and their successional status (Belnap, 2006). Pioneer or early successional biocrusts are composed mainly of bacteria, fungi and cyanobacteria (Büdel, 2005). In suitable climate conditions, after soil surfaces are stabilized by cyanobacteria, the lichens and bryophytes begin their colonization (Belnap, 2006), to form well-developed biocrusts, with the proportion of bacteria and cyanobacteria, algae, microfungi, lichens and bryophytes occurring in different combinations and abundances, depending on soils and climate (Büdel, 2005).

Although biocrusts contribute a minor proportion of the soil profile (less than one to a few millimeters in thickness), they play multiple roles, especially where water is scarce (Miralles-Mellado et al., 2011). At a fine scale, biocrusts can be considered as an ecological boundary because they control the flux of energy and materials in the interface between the atmosphere and the soil surface, as well as a soil and plant roots interface (Belnap et al., 2003b). Some of the functions that biocrusts influence include soil surface micro-topography (Rodríguez-Caballero et al., 2012), porosity (Miralles et al., 2012), infiltration (Eldridge et al., 2000; Xiao et al., 2011; Chamizo et al., 2012a; Rossi et al., 2012), water absorption and retention (Chamizo et al., 2012a),

* Corresponding author.
E-mail addresses: Jalil.Kaka@ut.ac.ir (J. Kakeh), mgorji@ut.ac.ir (M. Gorji), mycolich@yahoo.com (M. Sohrabi), atavili@ut.ac.ir (A. Tavili), pourbabaei@ut.ac.ir (A.A. Pourbabaee).

https://doi.org/10.1016/j.still.2018.04.007
Received 28 January 2017; Received in revised form 28 February 2018; Accepted 10 April 2018
0167-1987/

soil aggregation and stability (Chamizo et al., 2012b), sediment production (Chamizo et al., 2012a), evaporation, water and wind erosion (Belnap and Gillette, 1997), and nutrient retention (Reynolds et al., 2001). The presence of biocrusts have also been shown to increase fertility in plant interspaces in many ecosystems (Chamizo et al., 2012b), and can also alter local hydrology, leading that enhances water and nutrient availability, thereby promoting the establishment and development of vascular plant (Zhang et al., 2016).

Despite the documented importance of biocrusts globally (Belnap, 2006; Chamizo et al., 2012b; Bowker et al., 2013; Chen and Duan, 2015), few studies have been devoted to the influence of biocrusts on Iranian rangeland soils (e.g. Jafari et al., 2004). Turkmen Sahra, an important rangeland of Iran, is located in the Atrek area close to Alagol lake. This rangeland is severely degraded due to heavy grazing pressure and other human activities (Mirabzadeh-Ardakani, 2014). The aim of this study was to: 1) determine the effects of biocrusts on soil hydrology, 2) measure how biocrusts affect soil chemical and physical properties, and 3) document the vertical variation in soil physicochemical properties (at depths of 0–5 and 5–15 cm) for soils with and without biocrusts. To this end, the hypotheses that (a) biocrusts would affect soil hydrology with increasing infiltration rate, and (b) positively modify local hydrology, soil stability, nutrient retention, etc. by their presence, and that (c) soil physical and chemical properties would be different in soils covered with and without biocrusts, and (d) these differences would decrease with increasing depth, were tested.

2. Materials and methods

2.1. Study sites

The study was carried out in the Alagol rangelands of Turkmen Sahra around the lowlands of Alagol Lake, 60 km north of Gorgan, Golestan province, Northern Iran (37°15′–37°23′ N and 54°33′–54°39′ E) (Fig. 1). The plain of Turkmen Sahra is connected in the north with deserts of Karakum in Turkmenistan, in the east with the Kopet-Dag Mountains occurring on the border between Turkmenistan and Iran, in the south with the Hyrcanian)Caspian) mixed forests, and in the west with the Caspian Sea lowland wetlands. In general, the study area is physiographically a plateau with a 3–5% general slope and 8% side slope, at an altitude of 15 to 47 m above sea level. The Alagol rangelands in Turkmen Sahra comprise loess hills, and it is thought that the soil forming these hills originated in the Qara Qum (Karakum) Plain in Turkmenistan, from where it was transported by wind to Iran (Kehl et al., 2005). The soil type at our study sites is classified as loam, mixed, superactive, thermic Sodic Haplogypsides and the soil texture is loam (United States Department of Agriculture USDA, 2010). The soils are fertile, but vulnerable to erosion, land degradation, and desertification (Kehl et al., 2005). Compared to lowland soil, the soils in the study area (Fig. 3F) are well drained, with medium infiltration rates, and a greater depth to the water table. General properties of soil horizons at the study showed in Table 1 (Sarmadian, 1998).

The climate of the study area is continental and dry, with a mean annual precipitation of 273 mm, the highest rainfall occurring in January and February, and the lowest in July and August (Iranian Meteorological Organization (IRIMO). The mean annual temperature is 13.1 °C, the absolute max. and min. temperatures being 42.8 °C and −5.36 °C respectively. Annual potential evaporation is 1700 mm.

2.2. Vascular vegetation and types of biological soil crusts

There have only been two previous studies of the vascular vegetation of Alagol rangelands (Jafari et al., 2004; Mirdeylami et al., 2012). According to these studies, the vascular vegetation in our study area is dominated by Poaceae (15 species), Asteraceae (12 species), Fabaceae (8 species), Lamiaceae (8 species) and Brassicaceae (4 species). Some important vascular plants and biocrust lichens are listed in (Supplementary Information). Total ground cover was estimated at about 34%, of which 9% and 6% were mosses and lichens, respectively (Jafari et al., 2004). The collected biocrusts species specimens have been deposited in the Iranian Cryptogamic Herbarium (ICH) at the Iranian Research Organization for Science and Technology.

2.3. Soil sampling and soil properties determination

In order to investigate the effects of biocrusts on soil physicochemical characteristics, sampling was performed in four separate areas 1 km apart with similar climate, geology and topography. In each of the study areas, soils with plants and biocrusts were sampled from randomly established 100 m transects at four locations every 25 m, i.e. 25 m, 50 m, 75 m, 100 m at two depths (0–5 & 5–15 cm). A bare site adjacent to each of these four sampling locations was sampled (as shown in Fig. 3C and E). In all, 64 locations (4 sites × 4 sampling locations × 2 depths) were investigated.

In the laboratory, the soil samples were air-dried and sieved to 2 mm. Subsamples were mixed in a mechanical agate mortar to obtain the 0.5 mm particle size necessary for the determination of organic carbon and exchangeable cations. The following physical properties were determined: particle size distribution by the hydrometer method (Glendon, 1986); available water content (AWC) by difference between water content retained at 33 KPa and 1500 KPa, using a Richard's pressure-membrane extractor (Dane and Hopmans, 1986); wet aggregate stability (WAS) using the drop test (Kemper and Rosenau, 1986); aggregate size distribution using the geometric mean diameter (GMD) of the aggregates (Kemper and Rosenau, 1986), bulk density (ρb) (Black and Hartge, 1986) and infiltration using a double ring infiltrometer (Reynolds et al., 1986).

The following physicochemical properties were determined: soil acidity (pH) (McLean, 1982), calcium carbonate (Nelson, 1982) and electrical conductivity (EC) (Rhoades, 1982), as well as exchangeable sodium (Rhoades, 1982), calcium (Lanyon and Heald, 1982), and magnesium (Lanyon and Heald, 1982).

The following chemical properties were also analysed: soil organic carbon (SOC) (Nelson and Sommers, 1996); soil total nitrogen (STN) (Bremner and Mulvaney, 1982); available phosphorus (Olsen and Sommers, 1982), available potassium (Knudsen et al., 1982), extractable zinc (Baker and Amacher, 1982), extractable copper (Baker and Amacher, 1982), iron (Olson and Roscoe, 1982) and manganese (Robert and William, 1982).

2.4. Statistical analysis

To test the effects of biocrusts on soil properties, we applied nested design and the data were analyzed in SAS (Version 9.1.3). Nested design was used since there was one variable with two or more subvariables; this design tested significant variation among groups, subgroups within groups. The comparison of means among the areas with or without biocrusts was undertaken by Duncan's multiple range test ($P < 0.05$).

3. Results

3.1. Effects of biological soil crusts on soil physical properties

The presence of biocrusts had a significant effect on most of the physical properties measured (Table 2); there was no significant difference in clay, silt or sand content among the depths or the soil surface cover types, but bulk density in the surface (0–5 cm) was lower in the biocrusted soils (1.29 ± 0.06; Table 2).

Available water content was higher in surface soils under biocrusts, followed by subsurface soils under biocrusts. Both of these values were higher than those of soils without biocrusts, which did not differ from each other at either depth. Surface soil aggregates beneath biocrusts

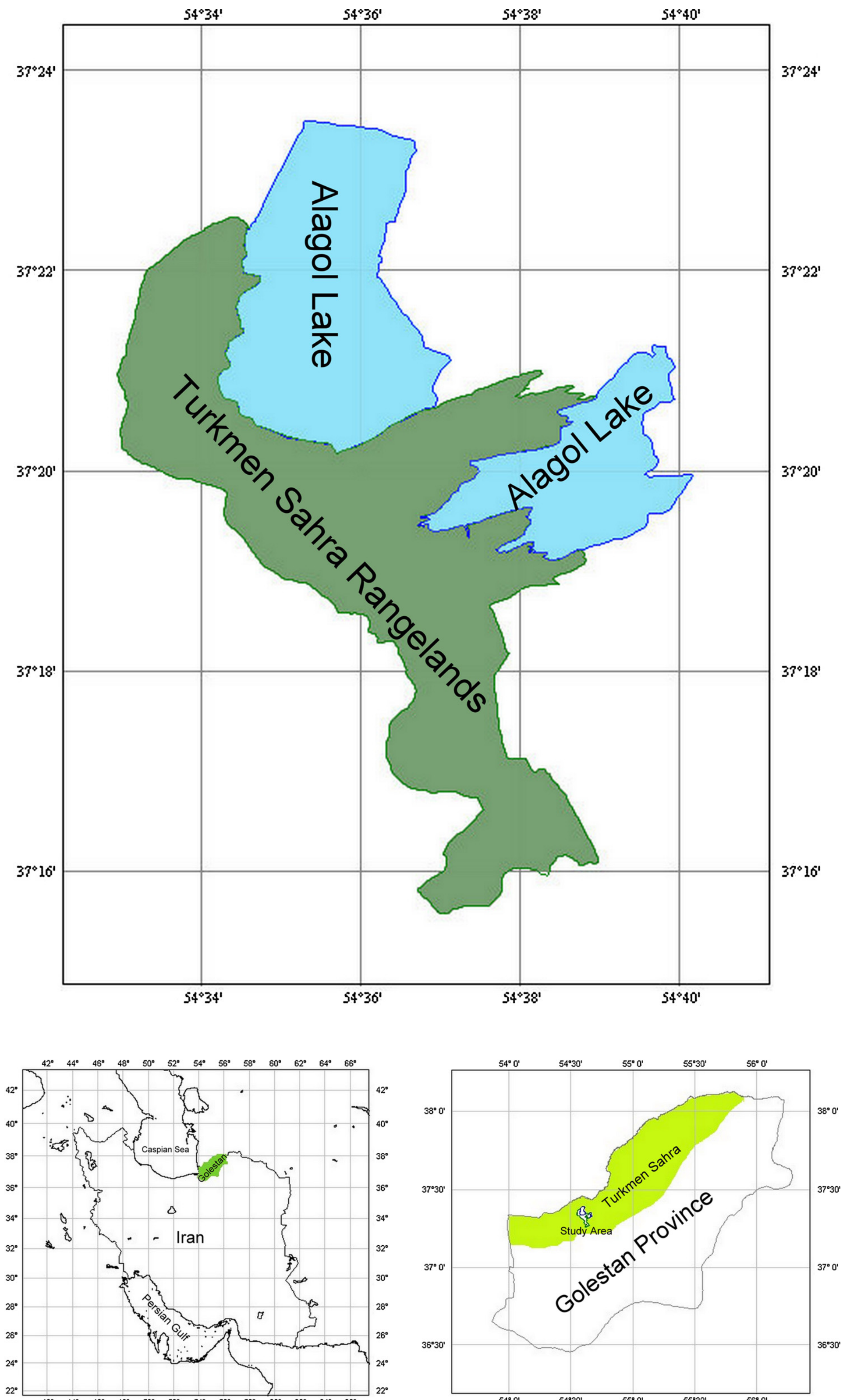

Fig. 1. Location of the study area in Golestan province, Iran.

had greater geometric mean diameter (GMD) and aggregate stability (WSA) than under bare soils.

Total and steady-state infiltration rates were about twice as high on bioencrusted surfaces than unencrusted surfaces (Fig. 2). At the beginning of the experiment, bioencrusted surfaces had infiltration rates of 5.2 mm min^{-1}, whereas unencrusted surfaces had rates of 2.2 mm min^{-1}; after 70–90 minutes, the final was respectively 1.6 and 0.81 mm min^{-1}.

3.2. Effects of biocrusts on soil physicochemical properties

Biocrusts had a significant effect on most physicochemical

Table 1
General properties of soil horizons at the study.

EC (dS m^{-1})	pH	N (%)	OC (%)	$CaCO_3$ (%)	ρb (Mg m^{-3})	Texture	Sand (%)	Silt (%)	Clay (%)	Depth (cm)	horizon
29.3	7.64	0.045	0.58	17	1.4	loam	37.6	41.9	20.5	0-25	A
33.7	7.28	0.017	0.14	15.8	1.5	loam	39.2	41.2	19.6	25-55	Bw
24.1	7.85	–	0.09	19.6	1.5	silt loam	30.8	52.8	16.4	55-125	Bky
20.6	8.1	–	0.04	18.7	1.3	silt loam	24.8	60.8	14.4	125-170	C

properties (Table 3). Soil pH under biocrusts was lower than that under bare soils. The pH under biocrusts was lower at the surface, but there was no difference between biocrusts and bare soils at 5–15 cm.

Calcium carbonate content was substantially lower in bioencrusted soils at both depths than in uncrusted soils. Electrical conductivity (dS/m), Ca, Mg, and Na concentrations (meq L^{-1}), the Na adsorption ratio and exchangeable Na percentages were all lower in surface soils covered with biocrusts than sub-surface soils. Values for non-biocrusted soils were greater than values for soils covered with biocrusts.

3.3. Effects of biological soil crusts on soil chemical properties

Biocrusts also had a significant effect on most chemical properties (Table 4); for example, organic carbon in biocrusted soils was higher than in non-biocrusted soils, and overall, surface soils had more organic carbon than sub-surface soils. Total N was higher in biocrusted surface soils than non-biocrusted surface soils or biocrusted sub-surface soils. Values of available P were significantly higher in biocrusted surface soils than bare soils, which were not significantly different from each other. Available K was not significantly different among any of the soils or depths tested.

Available Cu, Fe and Mn were higher in crusted soils at 0–5 cm depth than bare soils at the same depth. Conversely, Fe showed no significant differences in either crusted or bare sub-surface soils and available Zn was not significantly different among any of the tested soil samples.

4. Discussion

4.1. Physical properties

There are a few reports to show that biocrusts can affect the weathering of parent materials (Aghamiri and Schwartzman, 2002; Souza-Egipsy et al., 2004) and consequently soil formation and particle size distribution. Since our study area is dominated by fine-textured soils (Kehl et al., 2005) probably explains why biocrusts did not appear to cause any increase in silt and clay particles, as reported in other studies on sandy soils (e.g. Guo et al., 2008). Similar to our results, Chamizo et al. (2012b) did not find any significant differences in soil particle size distribution when bioencrusted surface soils (0–1 cm) were compared with sub-surface (1-5 cm) soils at Las Amoladeras in south-east Spain.

Bulk density was lower in bioencrusted surface soils at both measured depths, most likely due to the higher amount of SOC and greater pore space in these soils compared to the bare soils investigated. However, grazing in the study area, especially in the wet season, and

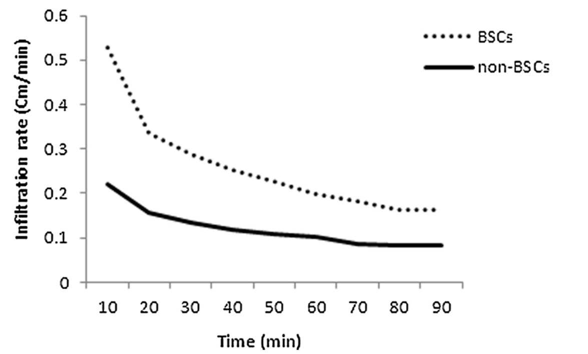

Fig. 2. Infiltration rate curves in soil surfaces with and without biocrusts.

lack of suitable vegetation cover on a non-biocrusted surface, leads to increased soil compaction and breakdown of surface aggregates, resulting in increased bulk density (Fig. 3A and B). It should be noted that in the study area grazing carried out especially in the wet season (November to April), which in this period, vascular plants growing on soils that have biocrusts. Therefore, due to the combining surface covered of biocrusts and vegetation cover with without biocrusts area, inevitably total area placed under impact grazing. Similar to our results, Guo et al. (2008) found bulk density decreased in topsoil under biocrusts, with values of 1.64, 1.60 and 1.56 g cm^{-3} in physical, algae and moss crusts, respectively.

Since GMD and WAS were higher in bioencrusted surface soils than non-biocrusted soils, several reasons that may explain this. First, larger well-developed biocrust organisms such as mosses, and lichens cover the soil surface, preventing raindrops from directly impacting the soil surface and thus detaching soil particles. Second, anchoring structures, such as rhizines in lichens and rhizoids in mosses, physically bind the soil particles (Bowker et al., 2008). Third, bioencrusted surface soils can be attributed to the higher soil OC content and consequently chemically bind the soil particles (Chamizo et al., 2012b).

Chaudhary et al. (2009) showed that vascular plants made the greatest contribution to sub-surface (below 15 cm) soil stability, while biocrusts were more effective for stabilizing surface soils (up to 0–15 cm). In our study, we confirmed this, and showed that aggregate stability in bioencrusted soil at depths (0–15 cm) was greater in non-covered soils. Our data show that bioencrusted soils had lower Na concentrations than non-bioencrusted soils. This would reduce the thickness of the diffusion double layer and lead to greater flocculation of the soil particles and thus greater aggregate stability. In non-bioencrusted soils, aggregate stability and GMD were lower at 0–5 cm than at 5–15 cm depths, probably due to over-grazing which causes aggregate

Table 2
Means comparison to evaluate the effects of biocrusts on soil physical properties.

Treatment	Depth (cm)	Clay (%)	Silt (%)	Sand (%)	ρb (Mg m^{-3})	AWC (%)	GMD (mm)	WAS (%)
biocrusts	0-5	18.21 ± 2.4a	47.08 ± 3.3a	34.71 ± 4.17a	1.29 ± 0.06b	10.41 ± 0.83a	2.51 ± 0.11a	66.13 ± 20a
	5-15	20.29 ± 4.2a	46.11 ± 4.7a	33.60 ± 5.6a	1.34 ± 0.05a	8.61 ± 0.37b	2.23 ± 0.12b	61.77 ± 1.02b
Non-biocrusts	0-5	22.11 ± 2.3a	43.03 ± 2.1a	34.86 ± 4.2a	1.42 ± 0.041a	5.98 ± 1.09c	1.25 ± 0.15d	35.29 ± 2.07d
	5-15	22.80 ± 2.0a	43.20 ± 3.3a	34.0 ± 4.82a	1.43 ± 0.062a	5.84 ± 0.53c	1.64 ± 0.16c	40.31 ± 2.05c

ρb = Bulk density; θm = Water Content; AWC = Available Water Content; GMD = Geometric Mean Diam. and WAS = Water Stable Aggregates.

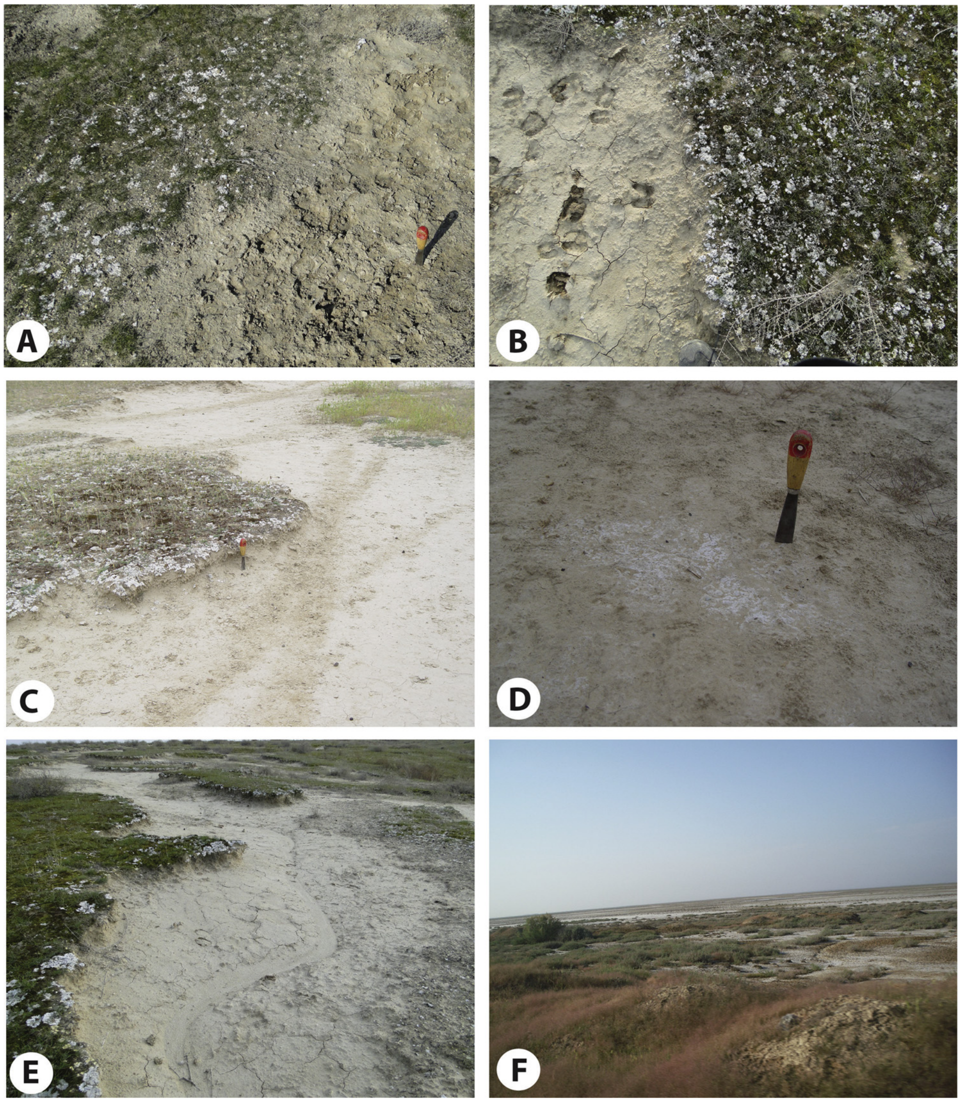

Fig. 3. Bio-encrusted and bare surface soils in the Alagol rangelands of Turkmen Sahra, NE Iran: A and B) Bare surface soil disturbance by livestock grazing, C) Topographic differences between bare and bioencrusted soils, D) Build-up of salinity in non-bioencrusted surface soils, E) Increasing surface roughness of bioencrusted soils reducing run-off velocity, and F) Accumulation of salts in the dry seasons in lowland saline wetlands near the sampling locations.

Table 3
Comparison of mean and standard deviation for evaluation effects of biocrusts and non-biocrusts on physicochemical properties of soils at two depths.

Treatment	Depth (cm)	pH	$CaCO_3$ (%)	EC (dS m^{-1})	Na (meq/lit)	Ca (meq/lit)	Mg (meq/lit)	SAR	ESP
biocrusts	0-5	7.36 ± 0.07c	10.27 ± 1.01b	2.19 ± 0.10d	16.49 ± 2.23d	2.63 ± 0.08d	3.95 ± 0.1d	9.09 ± 0.1d	11.99 ± 0.09d
	5-15	7.65 ± 0.16b	11.87 ± 1.80b	3.42 ± 11c	34.75 ± 2.17c	4.91 ± 0.13c	5.50 ± 0.09c	15.23 ± 0.08c	18.59 ± 0.07c
Non-biocrusts	0-5	8.15 ± 0.1a	16.36 ± 1.94a	17.15 ± 0.02b	166.42 ± 2.07b	19.30 ± 0.07b	22.98 ± 0.1b	36.19 ± 0.05b	35.18 ± 0.04b
	5-15	8.05 ± 0.16a	17.07 ± 2.43a	45.88 ± 0.03a	334.33 ± 2.08a	124.31 ± 0.09a	75.97 ± 0.09a	33.40 ± 0.04a	33.37 ± 0.03a

Table 4
Comparison of mean and standard deviation for evaluation effects of biocrusts and non-biocrusts on chemical properties of soils at two depths.

Treatment	Depth (Cm)	OC (%)	N (%)	C/N	P (mg/Kg)	K (mg/Kg)	Fe (mg/Kg)	Cu (mg/Kg)	Zn (mg/Kg)	Mn (mg/Kg)
biocrusts	0-5	2.19 ± 0.22a	0.15 ± 0.025a	14.6	22.86 ± 2.22a	248. 64 ± 20.5a	2.7 ± 0.02a	0.89 ± 0.14a	0.27 ± 0.01a	2.45 ± 0.06a
	5-15	1.72 ± 0.17b	0.06 ± 0.007b	28.66	18.42 ± 1.59b	256.85 ± 31.98a	2.04 ± 0.09b	0.80 ± 0.12b	0.23 ± 0.03a	2.42 ± 0.03a
Non-biocrusts	0-5	1.07 ± 0.18c	0.064 ± 0.021b	16.71	17.87 ± 2.37b	245.81 ± 19.45a	1.95 ± 0.1b	0.59 ± 0.13d	0.24 ± 0.02a	2.30 ± 0.03b
	5-15	0.96 ± 0.16c	0.046 ± 0.014b	20.86	17.85 ± 2.22b	234.86 ± 30.14a	1.91 ± 0.09b	0.71 ± 0.17c	0.21 ± 0.02a	1.75 ± 0.04c

disturbance and compact the soil surface more than sub-surface layers.

The influence of biocrusts on infiltration rate can be positive, negative or neutral (Chamizo et al., 2016). Positive impacts have been attributed to the enhanced microtopography caused mostly of lichen and mosses, macroporosity due to the formation and addition of soil aggregates by the filaments of biocrust organisms and polysaccharides secreted by them. Higher infiltration rates can increase available soil water, which increases soil invertebrate activity (Rossi et al., 2012); the latter increase the formation of macro-pores in the soil, thereby enhancing infiltration and available water (Chamizo et al., 2012a). Late successional biocrusts (e.g. those with mosses and lichens, such as found in our study area) have the most biomass and increased roughness and thus also have a high water-holding capacity. This delays runoff initiation and increases infiltration and soil water content. Infiltration is also increased on bioencrusted soils because the greater aggregation of fine soil particles creates channels for water to enter the soil. Biocrusts can also improve the cover of vascular plants which, together with biocrusts, creates a greater surface roughness at a larger scale, increasing the path length of water movement in compare to smooth surfaces or bare soil (Fig. 3E).

Our data show that biocrusts positively influenced infiltration rates, likely due to an increase in soil surface roughness, OC, WAS and GMD, and a decrease in bulk density. Eldridge et al. (2000) showed that soil surface disturbance by livestock grazing can reduce infiltration rates by destroying soil aggregates, consequently reducing macro-porosity and pore continuity to the soil surface. The heavy grazing in the Alagol rangelands of Turkmen Sahra is most likely responsible for the loss of biocrusts and the subsequent reduction in infiltration (Fig. 3A and B).

4.2. Physicohemical properties

In our study, some soil physicohemical properties such as pH, $CaCO_3$, EC, Na, Mg, Ca, SAR, ESP were lower under bioencrusted soils compared to non-bioencrusted soils. Soil pH under the bioencrusted areas was lower than non-bioencrusted soils. This may be a result of several processes and could be interpreted in several ways. Higher infiltration in bioencrusted soils, due to reduced bulk density and greater aggregates, may leach soluble salts and alkaline cations (Ca, Mg and Na) downward into the soil, resulting in a lower pH at soil surface and a higher pH at lower depths. Alternatively, higher microbial populations and higher respiration and carbon dioxide generation found in bioencrusted soils could decrease pH (Büdel, 2005; Lane et al., 2013).

Soil pH and salinity patterns at our site were very similar to Jalisco (Mexico) at the southernmost tip of the North American (see Concostrina-Zubiri et al., 2013). In the Alagol rangelands of Turkmen Sahra, the presence of crustose lichens such as *Diploschistes diacapsis, D. muscorum* and *Squamarina cartilaginea* most likely influenced soil pH and consequently reduced the concentration of elements causing soil salinity (i.e. Na, Ca) compared to other biocrust components and bare soils. The secretion of organic acids by these lichens, especially *Diploschistes diacapsis*, may explain the lower pH values and an overall higher nutrient availability. Concostrina-Zubiri et al. (2013) noted the presence of some lichens, such as *D. diacapsis* and *Lecidella* sp., was correlated with a decreased soil pH and marked differences in mineral nutrient concentration (i.e. decrease in Na, K and Fe and increase in Ca and Zn concentration compared to other biocrust components and bare soil). It is also known that respiring organisms, such as lichens and cyanobacteria, produce organic acids that can decrease soil pH (Leão et al., 2012).

In our study, soils lacking biocrusts had much higher values for saline and sodic properties such as EC, Mg, Ca, Na, SAR and ESP. Similarly, Abed et al. (2012) showed that bare soils had higher EC than bioencrusted soils. The most likely explanation for this is that non-biocrusted soils are microtopographically lower than bioencrusted soils (Fig. 3C and E). Ponding of water and subsequent evaporation in these areas would leave substantial amounts of salts behind. Over time, the salinity of these areas could build up to the levels observed in our study (Fig. 3D). These high levels would likely prevent the colonization of plants or biocrust organisms, thus leading to a positive feedback of further increases in salinity.

White or pale coloured lichen communities (e.g. *Buellia*, *Diploschistes* and *Squamarina* species) could mirror solar radiation and reduce soil temperature and consequently decreases evaporation in biocrusts areas. The recognized bioaccumulation ability of lichens and mosses (e.g. Aničić et al., 2009) is also important in this situation.

The other possible reason for saline and sodic properties is the geomorphology of the study area, as it is located between lowland saline wetlands of SE Caspian Sea and Alagol Lake (see Fig. 1). In the dry season, these lowland saline wetlands dry completely and salts accumulate at the soil surface (Fig. 3F). These salts are exposed to winds that can distribute them throughout the Alagol rangelands of Turkmen Sahra. The salty dusts which cover both biocrusts and bare soils are composed of alkaline-earth cations with a high ionic potential since they are highly water soluble and readily leach from soils (Bohn et al., 2002). Thus the increased infiltration of water in bioencrusted soils will increase leaching of the cations, and since Na has a lower electrical charge than Mg and Ca, it can migrate faster through the soil, resulting in lower salt concentrations at the soil surface covered of biocrusts compared to bare soil.

4.3. Chemical properties

In our study, some soil chemical properties such as total N, P, Fe, Cu, Mn were significantly higher under bioencrusted soils compared to uncrusted soils. Organic carbon was higher in bioencrusted surface soils at both measured depths, likely due to the ability of biocrusts to fix atmospheric C (Thomas et al., 2008; Zaady et al., 2000). This leads to enhanced biocrust biomass and thus OC in the surface soil layer (0–5 cm) (Chamizo et al., 2012b). An extensive cover of even a thin layer of photosynthetically active organisms can be an important basis for C input into the soil (Zaady et al., 2000). Biocrusts also produce and secrete extracellular polysaccharides into surrounding soils, increasing the soil C pool (Mager and Thomas, 2011).

As with OC, total N was higher in biocrust surface soils than in non-biocrusted surface soils or biocrust subsurface soils. Many components of biocrusts can also fix atmospheric N (Belnap et al., 2003c). In addition to vascular plants, mosses and lichens, some cyanolichens (e.g. *Collema* species) and cyanobacteria are distributed in the biocrust components of the study area and also contribute atmospheric nitrogen fixation. In general, there is a positive correlation between C and N fixation. A correlated high organic carbon and nitrogen content under biocrusts in other studies (Chamizo et al., 2012b; Mager and Thomas, 2011; Miralles et al., 2012) support our results.

Our results showed an increase in available P in the surface soils covered by biocrusts. Lichenized and non-lichenized fungi secrete phosphatases which may have increased available P by dissolving the P-$CaCO_3$ bond that often makes P biologically unavailable in high pH soils (Harper and Marble, 1988). In several studies (e.g. Arnesen et al., 2007; Benner and Vitousek, 2012) it was shown that lichens and bryophytes contribute to soil fertility by increasing available P by fixing N. Furthermore, lichens such as *Diploschistes diacapsis* reduced phosphatase activity which may lead to a higher soil P concentration (Concostrina-Zubiri et al., 2013).

The relationship between a number of nutrients such as Ca, Cu, Na, and to a lesser extent Mg and Zn, are bonded to exterior cell walls of lichens. When a lichen is wetted, these nutrients are washed from it and become available to soil biota (Williams, 1994). In addition, cyanobacteria secrete peptide nitrogen and riboflavin, which together with sidrochromes, form complexes with tri-calcium phosphate, Cu, Zn, Ni and ferric iron, keeping them available for plants. Soil organic matter strongly adsorbs Fe^{2+}, Cu^{2+}, Zn^{2+} and other transition metal ions, probably by acting as chelaters. Many chelates are water soluble and

keep ions available for uptake by vascular plants and other organisms (Bohn et al., 2002).

5. Conclusions

The presence of well-developed biocrusts in the Alagol rangelands of Turkmen Sahra was associated with marked changes in the physical and chemical properties of soil, but most of these effects were confined to the surface layers (0–5 cm). Our study reinforces the notion that biocrusts are important for maintaining and improving the soil condition. In general, in the Alagol rangelands of Turkmen Sahra, physicochemical property measurements were higher in bio-encrusted surface soils when compared to the bare soil at the same depth. As the presence of biocrusts generally increased the positive qualities of the soil, it is suggested that they could be used as a qualitative indicator of soil quality in rangelands. Biocrusts, by protecting soil against corrosive forces, reduce rangeland degradation. Their presence plays an essential role in soil stability, reduction of salinity, water availability and enhancement of soil fertility in the arid and semi-arid Alagol rangelands of Turkmen Sahra where these sources are essential for the biological and environmental functions in the soil.

Acknowledgements

We are grateful to Prof. Jayne Belnap (US Geological Survey, USA), Dr Sonia Chamizo (Universidad de Almería, Spain) and Dr Roger Rosentreter (Boise State University, USA), Dr. Steven D. Warren (US Forest Service, USA) and Dr. David Eldridge (University of New South Wales, Australia) for their guidance and helpful criticisms, to anonymous referees for valuable comments and suggestions that helped to improve its quality, and to Prof. Mark Seaward (University of Bradford, UK) who kindly provided linguistic corrections and helpful criticism of a final draft of the MS.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.still.2018.04.007.

References

Abed, R.M., Al-Sadi, A.M., Al-Shehi, M., Al-Hinai, S., Robinson, M.D., 2012. Diversity of free-living and lichenized fungal communities in biological soil crusts of the Sultanate of Oman and their role in improving soil properties. Soil Biol. Biochem. 57, 695–705.
Aghamiri, R.R., Schwartzman, D.W., 2002. Weathering rates of bedrock by lichens: a mini watershed study. Chem. Geol. 188, 249–259.
Aničić, M., Tasić, M., Frontasyeva, M., Tomašević, M., Rajšić, S., Strelkova, L., Popović, A., Steinnes, E., 2009. Active biomonitoring with wet and dry moss: a case study in an urban area. Environ. Chem. Lett. 7, 55–60.
Arnesen, G., Beck, P.S., Engelskjøn, T., 2007. Soil acidity, content of carbonates, and available phosphorus are the soil factors best correlated with alpine vegetation: evidence from Troms, North Norway. Arct. Antarct. Alp. Res. 39, 189–199.
Baker, D.E., Amacher, M.C., 1982. Nickel, copper, zinc, and cadmium. Methods of Soil Analysis. Part 2. Chemical and Microbiological Properties. American Society of Agronomy-Soil Science Society of America, Madison, pp. 595–624.
Belnap, J., 2003c. Factors influencing nitrogen fixation and nitrogen release in biological soil crusts. In: Belnap, J., Lange, O. (Eds.), Biological Soil Crusts: Structure, Function, and Management. Springer-Verlag, Berlin, pp. 241–261.
Belnap, J., 2006. The potential roles of biological soil crusts in dryland hydrologic cycles. Hydrol. Process. 20, 3159–3178.
Belnap, J., Büdel, B., Lange, O., 2003a. Biological soil crusts: characteristics and distribution. In: Belnap, J., Lange, O. (Eds.), Biological Soil Crusts: Structure, Function, and Management. Springer-Verlag, Berlin, pp. 3–30.
Belnap, J., Gillette, D., 1997. Disturbance of biological soil crusts: impacts on potential wind erodibility of sandy desert soils in southeastern Utah. Land Degrad. Dev. 8, 355–362.
Belnap, J., Hawkes, C.V., Firestone, M.K., 2003b. Boundaries in miniature: two examples from soil. BioScience 53, 739–749.
Benner, J.W., Vitousek, P.M., 2012. Cyanolichens: a link between the phosphorus and nitrogen cycles in a Hawaiian montane forest. J. Trop. Ecol. 28, 73–81.
Black, G., Hartge, K., 1986. Bulk density. Methods of Soil Analysis. Part 1. Physical and Mineralogical Properties, Including Statistics of Measurement and Sampling. American Society of Agronomy-Soil Science Society of America, Madison, pp. 363–376.
Bohn, H.L., Myer, R.A., O'Connor, G.A., 2002. Soil Chemistry, 3rd ed. John Wiley, New York, pp. 1–307.
Bowker, M.A., Eldridge, D.J., Val, J., Soliveres, S., 2013. Hydrology in a patterned landscape is co-engineered by soil-disturbing animals and biological crusts. Soil Biol. Biochem. 61 (Suppl. C), 14–22.
Bowker, M.A., Koch, G.W., Belnap, J., Johnson, N.C., 2008. Nutrient availability affects pigment production but not growth in lichens of biological soil crusts. Soil Biol. Biochem. 40, 2819–2826.
Bremner, J., Mulvaney, C., 1982. Nitrogen-total. Methods of Soil Analysis. Part 2. Chemical and Microbiological Properties. American Society of Agronomy-Soil Science Society of America, Madison, pp. 595–624.
Büdel, B., 2005. Microorganisms of biological crusts on soil surfaces. In: In: Varma, A., Buscot, F. (Eds.), Microorganisms in Soils: Roles in Genesis and Functions, vol. 3. Springer, Berlin, pp. 307–323.
Chamizo, S., Belnap, J., Eldridge, D.J., Cantón, Y., Issa, O.M., 2016. The role of biocrusts in arid land hydrology. Biological Soil Crusts: An Organizing Principle in Drylands. Springer, pp. 321–346.
Chamizo, S., Cantón, Y., Lázaro, R., Solé-Benet, A., Domingo, F., 2012a. Crust composition and disturbance drive infiltration through biological soil crusts in semiarid ecosystems. Ecosystems 15, 148–161.
Chamizo, S., Cantón, Y., Miralles, I., Domingo, F., 2012b. Biological soil crust development affects physicochemical characteristics of soil surface in semiarid ecosystems. Soil Biol. Biochem. 49, 96–105.
Chaudhary, V.B., Bowker, M.A., O'Dell, T.E., Grace, J.B., Redman, A.E., Rillig, M.C., Johnson, N.C., 2009. Untangling the biological contributions to soil stability in semiarid shrublands. Ecol. Appl. 19 (1), 110–122.
Chen, X., Duan, Z., 2015. Impacts of soil crusts on soil physicochemical characteristics in different rainfall zones of the arid and semi-arid desert regions of northern China. Environmental Earth Sciences 73 (7), 3335–3347.
Concostrina-Zubiri, L., Huber-Sannwald, E., Martínez, I., Flores Flores, J., Escudero, A., 2013. Biological soil crusts greatly contribute to small-scale soil heterogeneity along a grazing gradient. Soil Biol. Biochem. 64, 28–36.
Dane, J.H., Hopmans, J.W., 1986. Water retention and storage: pressure plate extractor. Methods of Soil Analysis. Part 1. Physical and Mineralogical Properties, Including Statistics of Measurement and Sampling. American Society of Agronomy-Soil Science Society of America, Madison, pp. 1–770.
Eldridge, D.J., Zaady, E., Shachak, M., 2000. Infiltration through three contrasting biological soil crusts in patterned landscapes in the Negev, Israel. Catena 40, 323–336.
Fang, H.Y., Cai, Q.G., Chen, H., Li, Q.Y., 2007. Mechanism of formation of physical soil crust in desert soils treated with straw checkerboards. Soil Tillage Res. 93, 222–230.
Glendon, W.G., 1986. Particle-size analysis. Methods of Soil Analysis. Part 1. Physical and Mineralogical Properties, Including Statistics of Measurement and Sampling. American Society of Agronomy-Soil Science Society of America, Madison, pp. 545–567.
Guo, Y., Zhao, H., Zuo, X., Drake, S., Zhao, X., 2008. Biological soil crust development and its topsoil properties in the process of dune stabilization, Inner Mongolia, China. Environ. Geol. 54, 653–662.
Harper, K.T., Marble, J.R., 1988. A role for nonvascular plants in management of arid and semiarid rangelands. In: Tueller, P.T. (Ed.), Vegetation Science Applications for Rangeland Analysis and Management. Kluwer Academic, Dordrecht, pp. 135–169.
Jafari, M., Tavili, A., Zargham, N., Heshmati, G.A., Chahouki, M.Z., Shirzadian, S., Azarnivand, H., Zehtabian, G.R., Sohrabi, M., 2004. Comparing some properties of crusted and uncrusted soils in Alagol region of Iran. Pak. J. Nutr. 3, 273–277.
Kehl, M., Sarvati, R., Ahmadi, H., Frechen, M., Skowronek, A., 2005. Loess paleosol-sequences along a climatic gradient in Northern Iran. Eiszeitalter und Gegenwart 55, 149–173.
Kemper, W., Rosenau, R., 1986. Aggregate stability and size distribution. Methods of Soil Analysis. Part 1. Physical and Mineralogical Properties, Including Statistics of Measurement and Sampling. American Society of Agronomy-Soil Science Society of America, Madison, pp. 425–442.
Knudsen, D., Peterson, G., Pratt, P., 1982. Lithium, sodium, and potassium. Methods of Soil Analysis. Part 2. Chemical and Microbiological Properties. American Society of Agronomy-Soil Science Society of America, Madison, Wisconsin, pp. 225–246.
Lane, R.W., Menon, M., McQuaid, J.B., Adams, D.G., Thomas, A.D., Hoon, S.R., Dougill, A.J., 2013. Laboratory analysis of the effects of elevated atmospheric carbon dioxide on respiration in biological soil crusts. J. Arid Environ. 98, 52–59.
Lanyon, L.E., Heald, W.R., 1982. Magnesium, calcium, strontium, and barium. Methods of Soil Analysis. Part 2. Chemical and Microbiological Properties. American Society of Agronomy-Soil Science Society of America, Madison, pp. 247–262.
Leão, P.N., Engene, N., Antunes, A., Gerwick, W.H., Vasconcelos, V., 2012. The chemical ecology of cyanobacteria. Nat. Prod. Rep. 29, 372–391.
Mager, D.M., Thomas, A.D., 2011. Extracellular polysaccharides from cyanobacterial soil crusts: a review of their role in dryland soil processes. J. Arid Environ. 75, 91–97.
Mclean, E., 1982. Soil pH and lime requirement. Methods of Soil Analysis. Part 2. Chemical and Microbiological Properties. American Society of Agronomy-Soil Science Society of America, Madison, pp. 199–224.
Mirabzadeh-Ardakani, P., 2014. Political Ecology of Conservation in the 'Alagol, Ulmagol, and Ajigol'Glocal Wetlands. Carleton University Ottawa, Turkmen Sahra, Northeast Iran Postdoctoral thesis.
Miralles, I., Domingo, F., García-Campos, E., Trasar-Cepeda, C., Leirós, M.C., Gil-Sotres, F., 2012. Biological and microbial activity in biological soil crusts from the Tabernas desert, a sub-arid zone in SE Spain. Soil Biol. Biochem. 55, 113–121.
Miralles-Mellado, I., Cantón, Y., Solé-Benet, A., 2011. Two-dimensional porosity of crusted silty soils: indicators of soil quality in semiarid rangelands? Soil Sci. Soc. Am. J. 75, 1330–1342.

Mirdeylami, S.Z., Heshmati, G., Barani, H., Hemmatzade, Y., 2012. Environmental factors affecting ecological sites distribution of Kachik rangeland, Marave Tappe. Iranian J. Range Desert Res. 19, 334–343.

Nelson, D.W., Sommers, L.E., 1996. Total carbon, organic carbon, and organic matter. Methods of Soil Analysis. Part 2. Chemical and Microbiological Properties. American Society of Agronomy-Soil Science Society of America, Madison, pp. 961–1010.

Nelson, R., 1982. Carbonate and gypsum. Methods of Soil Analysis. Part 2. Chemical and Microbiological Properties. American Society of Agronomy-Soil Science Society of America, Madison, pp. 181–197.

Olsen, S.R., Sommers, L.E., 1982. Phosphorus. Methods of Soil Analysis. Part 2. Chemical and Microbiological Properties. American Society of Agronomy-Soil Science Society of America, Madison, pp. 1035–1049.

Olson, R.V., Roscoe, E.J.R., 1982. Iron. Methods of Soil Analysis. Part 2. Chemical and Microbiological Properties. American Society of Agronomy-Soil Science Society of America, Madison, pp. 323–336.

Reynolds, R., Belnap, J., Reheis, M., Lamothe, P., Luiszer, F., 2001. Aeolian dust in Colorado Plateau soils: nutrient inputs and recent change in source. Proc. Natl. Acad. Sci. 98, 7123–7127.

Reynolds, W.D., Elrick, D.E., Youngs, E.G., 1986. Single-Ring and double-or concentric-ring infiltrometers. Methods of Soil Analysis. Part 1. Physical and Mineralogical Properties, Including Statistics of Measurement and Sampling. American Society of Agronomy-Soil Science Society of America, Madison, pp. 818–820.

Rhoades, J., 1982. Soluble salts. Methods of Soil Analysis. Part 2. Chemical and Microbiological Properties. American Society of Agronomy-Soil Science Society of America, Madison, pp. 167–179.

Robert, P.G., William, H.P., 1982. Manganese. Methods of Soil Analysis. Part 2. Chemical and Microbiological Properties. American Society of Agronomy-Soil Science Society of America, Madison, pp. 313–322.

Rodríguez-Caballero, E., Cantón, Y., Chamizo, S., Afana, A., Solé-Benet, A., 2012. Effects of biological soil crusts on surface roughness and implications for runoff and erosion. Geomorphology 145–146, 81–89.

Rossi, F., Potrafka, R.M., Pichel, F.G., De Philippis, R., 2012. The role of the exopolysaccharides in enhancing hydraulic conductivity of biological soil crusts. Soil Biol. Biochem. 46, 33–40.

Sarmadian, F., 1998. Soil Genesis, Classification and Land Suitability Assessment in Different Climates of Gorgan and Gonbad in North of Iran. Natural Resources Faculty, University of Tehran Ph.D thesis (in Persian).

Souza-Egipsy, V., Wierzchos, J., Sancho, C., Belmonte, A., Ascaso, C., 2004. Role of biological soil crust cover in bioweathering and protection of sandstones in a semi-arid landscape (Torrollones de Gabarda, Huesca, Spain). Earth Surf. Process. Landforms 29, 1651–1661.

Thomas, A.D., Hoon, S.R., Linton, P.E., 2008. Carbon dioxide fluxes from cyanobacteria crusted soils in the Kalahari. Appl. Soil Ecol. 39 (3), 254–263.

United States Department of Agriculture USDA, 2010. Keys to Soil Taxonomy, 11th ed. United States Department of Agriculture and Natural Resources Conservation Service, Washington.

Williams, J.D., 1994. Microbiotic Crusts: A Review. (Final Draft). U.S.D.A., Eastside Ecosystem Management Project Report. unpublished data. .

Xiao, B., Wang, Q.H., Zhao, Y.G., Shao, M.A., 2011. Artificial culture of biological soil crusts and its effects on overland flow and infiltration under simulated rainfall. Appl. Soil Ecol. 48, 11–17.

Zaady, E., Kuhn, U., Wilske, B., Sandoval-Soto, L., Kesselmeier, J., 2000. Patterns of CO_2 exchange in biological soil crusts of successional age. Soil Biol. Biochem. 32, 959–966.

Zhang, Y., Aradottir, A.L., Serpe, M., Boeken, B., 2016. Interactions of biological soil crusts with vascular plants. Biological Soil Crusts: An Organizing Principle in Drylands. Springer, pp. 385–406.