IT ISSN 0391 - 9838

GEOGRAFIA FISICA e DINAMICA QUATERNARIA

Bollettino del Comitato Glaciologico Italiano - ser. 3

An international Journal published under the auspices of the
Rivista internazionale pubblicata sotto gli auspici di

Associazione Italiana di Geografia Fisica e Geomorfologia
and (e) Consiglio Nazionale delle Ricerche (CNR)

recognized by the (*riconosciuta da*)

International Association of Geomorphologists (IAG)

volume 42 (1)
2019

COMITATO GLACIOLOGICO ITALIANO - TORINO
2019

GEOGRAFIA FISICA E DINAMICA QUATERNARIA

A journal published by the Comitato Glaciologico Italiano, under the auspices of the Associazione Italiana di Geografia Fisica e Geomorfologia and the Consiglio Nazionale delle Ricerche of Italy. Founded in 1978, it is the continuation of the «Bollettino del Comitato Glaciologico Italiano». It publishes original papers, short communications, news and book reviews of Physical Geography, Glaciology, Geomorphology and Quaternary Geology. The journal furthermore publishes the annual reports on italian glaciers, the official transactions of the Comitato Glaciologico Italiano and the Newsletters of the Intemational Association of Geomorphologists. Special issues, named «Geografia Fisica e Dinamica Quaternaria - Supplementi», collecting papers on specific themes, proceedings of meetings or symposia, regional studies, are also published, starting from 1988. The language of the journal is English, but papers can be written in other main scientific languages.

Rivista edita dal Comitato Glaciologico Italiano, sotto gli auspici dell'Associazione Italiana di Geografia Fisica e Geomorfologia e del Consiglio Nazionale delle Ricerche. Fondata nel 1978, è la continuazione del «Bollettino del Comitato Glaciologico Italiano». La rivista pubblica memorie e note originali, recensioni, corrispondenze e notiziari di Geografia Fisica, Glaciologia, Geomorfologia e Geologia del Quaternario, oltre agli Atti ufficiali del C.G.I., le Newsletters della I.A.G. e le relazioni delle campagne glaciologiche annuali. Dal 1988 vengono pubblicati anche volumi tematici, che raccolgono lavori su argomenti specifici, atti di congressi e simposi, monografie regionali sotto la denominazione «Geografia Fisica e Dinamica Quaternaria - Supplementi». La lingua usata dalla rivista è l'Inglese, ma gli articoli possono essere scritti anche nelle altre principali lingue scientifiche.

Indexed/Abstracted in: Bibliography & Index of Geology (GeoRef); GeoArchive (Geosystem); GEOBASE (Elsevier); *Geographical Abstract*: *Physical Geography* (Elsevier); GeoRef; Geotitles (Geosystem); Hydrotitles and Hydrology Infobase (Geosystem); Referativnyi Zhurnal.
Geografia Fisica e Dinamica Quaternaria has been included in the Thomson ISI database beginning with volume 30 (1) 2007 and now appears in the Web of Science, including the Science Citation Index Expanded (SCIE), as well as the ISI Alerting Services.

HOME PAGE: http://gfdq.glaciologia.it/ - CONTACT: gfdq@dst.unipi.it

Printed with the financial support from (pubblicazione realizzata con il contributo finanziario di):

– Comitato Glaciologico Italiano
– Associazione Italiana di Geografia Fisica e Geomorfologia
– Ministero dell'Istruzione, Università e Ricerca
– Consiglio Nazionale delle Ricerche
– Club Alpino Italiano

Geogr. Fis. Dinam. Quat.
42 (2019). 99-112, 5 figg., 6 tabb.

DOI 10.4461/ GFDQ.2019.42.8

MAHVAN HASSANZADEH BASHTIAN [1], ADEL SEPEHR [1*],
MASOUMEH BAHREINI [2] & MOHAMMAD FARZAM [3]

MICROGEOMORPHOLOGY RELATED SOIL CHARACTERISTICS DETERMINE THE HETEROGENEITY OF BIOLOGICAL SOIL CRUST COMMUNITIES

ABSTRACT: HASSANZADEH BASHTIAN M., SEPEHR A., BAHREINI M. & FARZAM M., *Microgeomorphology related soil characteristics determine the heterogeneity of biological soil crust communities.* (IT ISSN 0391-9838, 2019).

We examined how biological soil crust (BSC) communities are affected by micro-geomorphology and soil characteristics in an arid ecosystem in northeastern Iran. Sampling was carried out systematically in the summer of 2016 along a geomorphic gradient within an alluvial fan by using micro-scale plots (0.25 m^2) and soil samples from the top soil layer (0-5 cm). According to the geomorphologic features and particle size distribution, the landform surfaces were divided into three units across the topographic gradient. From top downstream: Unit 1 involved coarse particles, Unit 2 included medium, and unit 3 comprised fine deposits., A total of 16 samples were taken for each unit (48 samples in total) along the alluvial fan from the apex to the base sector. The results indicated that micro-geomorphic and soil characteristics play an important role in the development of biological soil crust (BSC) micro-habitats. Decreasing content of calcium carbonate, pH, and soil salinity versus increasing soil moisture and clay content along the gradient of the alluvial fan showed a relevant correlation with increased BSCs coverage. BSCs increased along the landform gradient, although their diversity tended to decrease; in that way complex communities in the apex (Unit 1) involved cyanobacteria, lichen, mosses, and algae, while the dominant BSCs in the base (Unit 3) included moss species.

KEY WORDS: Alluvial fan, Biological Soil Crusts (BSCs), Microgeomorphology, Soil heterogeneity.

[1] *Department of Desert and Arid Zones Management, Ferdowsi University of Mashhad, Mashhad, Iran.*
[2] *Department of Biology, Ferdowsi University of Mashhad, Mashhad, Iran.*
[3] *Department of Watershed and Rangelands Management, Ferdowsi University of Mashhad, Mashhad, Iran.*
* *Corresponding author: A. SEPHER (adelsepehr@um.ac.ir)*

This research was supported by the financial grant 3/41505 from the Ferdowsi University of Mashhad, Iran. The Authors are thankful to the Mr. Parvian, responsible for NRE lab, for his support. Supplementary material (Figs S1-S4) is available at: http://gfdq.glaciologia.it/issues/

INTRODUCTION

BSCs consist of tiny organisms such as cyanobacteria, algae, lichens, mosses and other close ties that form a coherent horizontal layer with particles of soil surface (Li & *alii*, 2005; Friedmann & Galun, 1974; Belnap & Gardner, 1993; Williams & *alii*, 2012). BSCs vary widely in biotic combinations and surface morphology, crusts can possess up to 70% of the living soil cover in arid landscapes (Belnap, 1994). They are usually widespread under dryland conditions (Belnap, 2006; Büdel & *alii*, 2009). Biocrust cover is diverse across spatial scales (from centimeters to kilometers), and it could depend not only on the surrounding vascular vegetation cover but also on soils and microgeomorphology or terrains in arid, semi-arid and temperate environments (Evans & Johansen, 1999; Ullmann & Büdel, 2003; Kidron & *alii*, 2009; Bowker & *alii*, 2016; Seitz & *alii*, 2017). Different BSCs distributions are related to the microclimatic gradient under the influence of elevation and terrain (Kutiel & *alii*, 1998), different geomorphic regions (Eldridge, 1999), various aspects and soil types (George & *alii*, 2000; Bu & *alii*, 2016). As a result, the development of BSCs characterized by a high complexity and spatial heterogeneity with many microclimatic and micro-topographic factors, is of great importance to conduct studies on the spatial distribution of BSCs (Bu & *alii*, 2013; Pietrasiak & *alii*, 2014; Williams & *alii*, 2013).

There is a nearby relationship between soil physicochemical properties, denudation processes and BSCs. They generally reduce erosion (Longton, 1997; Belnap & Gillette 1998; Belnap & Lange 2003; Cornelissen & *alii* 2007; McKenna Neuman & *alii*, 1996), runoff and redistribution of water and soil surface stability (Goudie & Middleton, 2006), and also reduce pH and increase the availability of nutrients (Kleiner & Harper, 1977, Evans & Belnap, 1999). Natural nitrogen cycles are very important in soil fertility and preventing desertification (Webb & *alii*, 2009). BSCs provide the required nitrogen (Belnap & Long, 2003) for different organisms of soil.

The evolution of BSCs has a certain role in improving the physicochemical and biological properties of soils. The development of soil crusts can increase the growth of microorganisms and, thus improve the soil microenvironment and ecological restoration in the arid and semi-arid region (Niu & *alii* 2017). Studies indicate a significant correlation between morphological changes and soil physicochemical and biological properties (Chen & *alii*, 2007; Laity, 2006), and any environment indicates the interplay of BSCs relative to geomorphic or physical soil-forming processes that could forcefully influence on the crust establishment and propagation (Wang & *alii*, 2007; Bowker & Belnap, 2008; Li & *alii*, 2010).

The objectives of this study were to investigate (1) the geomorphic effects on BSC distribution along an alluvial fan and (2) the relationships between soil characteristics and BSC distribution.

STUDY SITE

The study site in an arid alluvial fan is located in Khorasan Razavi province, northeastern Iran, at Binaloud hillslopes, approximately within 36° 10′ N and 58° 59′ E (fig. 1). Mean annual temperature is 14.2 °C, and mean annual precipitation is 247.4 mm (the thirty-year average from Neyshabur meteorology station). This alluvial fan consists of debris flow deposits. Debris flow processes are one of the most important geomorphic processes in many arid and semi-arid regions. The mass movement of rock, mudflow, soil and water along the gradient (Staley & *alii*, 2006) make this process. The studied fan covers an area of 59 ha at a mean elevation of 3060 m asl. Deposits and formations are mainly related to the Quaternary evolution. Alluvial deposits consist of limestone, sandstone, and quartzite.

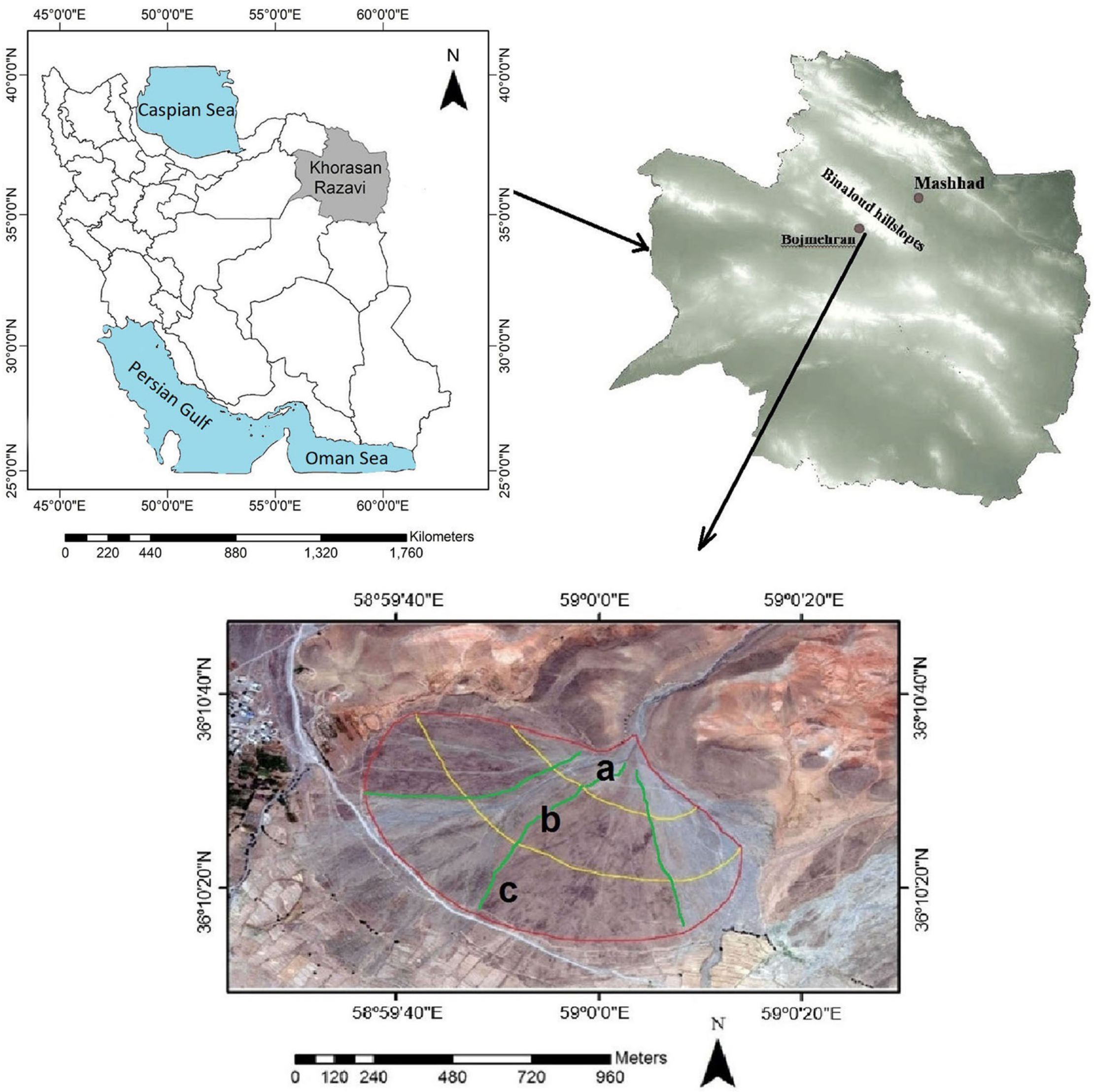

FIG. 1 - Location of the study area, (a) Unit 1, (b) Unit 2 and (c) Unit 3.

MATERIALS AND METHODS

Field methods

Based on field observations were identified the geomorphologic surfaces on the landform, which were divided into three units from top to downstream according to particle size distribution and geomorphological properties (three altitudinal belts). Indeed, in alluvial fans, the particle size distribution often changes not only downstream, but also laterally as a consequence of the typical fan-shaped distributary pattern changing over time. Fig. 1 highlights a certain radial distribution of units where different colors show four sectors on the alluvial fan. Each part separated by the four colors in the units was called macro-plot. As a result, each units can be divided into four macro-plots. Sampling was carried out systematically along a sequence of landforms in 2016, using quadrats of 0.25 m^2. Samples were taken from the topsoil layer (0-5 cm depth). The sampling quadrats were established randomly within each macro-plot with a total number of 48.

Morphometric and geomorphic characteristics of landform surface in each quadrat were measured in the field and on digital images, including: micro-topography (surface roughness index), covering of clasts, including cobble (75-160 mm) and gravel (2-75 mm) based on the USDA classification system, the percentage of bare soil, density of rocky surfaces, length and width variation of clasts, elevation and slope. A 50 cm tape was placed at the center of each quadrat, length and width of each clast touching the tape was measured (Folk, 1980). Clast sorting was calculated using Folk's logarithmic transformation criteria and transformed to the ϕ-scale (Folk, 1980). High values represent a low degree of sorting, i.e., a larger spread of clast sizes. Low values of sorting are obtained when most of the clasts have the same dimensions. Phi scale skewness and kurtosis were calculated to interpret the clast frequency distribution (Folk, 1980). Surface roughness describes the micro-topography of a site and was recorded by placing a bar roughness tester on the 50 cm tape and calculated using the methodology of Allmaras & *alii* (1966). The roughness bars used in this study were 2 cm and the height of 26 points was recorded in each 50 cm transect.

Estimation of the size of clast (length and width) was performed using ARC GIS 10.3 software. In this way, the digital images prepared from each quadrat were first georeferenced, then stones investigated whit the tools editor, and mean, median, sorting, skewness and kurtosis of clast were calculated.

Laboratory methods

The collected soil samples taken from surface layer (0-5cm) were air-dried and sieved with a 2 mm mesh. Soil texture was determined using a hydrometer (ASTM 152H) (Bouyoucos, 1962). pH was calculated with a 1:1 soil–water suspension by a pH-meter (Jenway Inc, England); electrical conductivity (EC) measured with a 1:1 soil–water suspension by an EC-meter (Jenway Inc, England); soil organic carbon (SOC) was estimated by the dichromate oxidation method (Nelson & Sommers, 1982); total nitrogen was measured by the Kjeldahl method (V50) (Bremner & Mulvaney, 1982); phosphorus, potassium and sodium were measured by the methods described by Knudsen & *alii* (1982) and Olsenard & Sommers (1982); calcium and magnesium were measured by the complex-metric method (Tucker & Kurtz, 1961); calcium carbonate measured with a calcimeter Scheibler system 08.53, and soil moisture content in the surface soil (depth 0-10 cm) was calculated by the weight method (oven-dry method) (Black, 1965).

Before sampling, the soil surface was sprayed with deionized water so that BSCs became visible. Lichen and moss specimens were identified in situ, but small pieces of thalli were collected, and cyanobacteria and algae samples were taken to the laboratory and were examined by light microscopy for species identification. Biological characterization included determining abundance and diversity of BSC community types estimated using a plot of 0.25 square meters. To identify BSC community, the methodology of Pietrasiak & *alii* (2011a, 2013) was used. The BSCs involve algae or cyanobacteria crust, cyanolichen crust, green algae lichen crust and moss crust (tab. 1). To investigate BSCs on the soil surface, a scanning electron microscope (SEM) (Leo-Germany 1450VP) was used on natural biocrust samples for each sampling site. The morphology characteristics of cyanobacteria and green algae were carefully evaluated by an optical microscope (magnifications 400-1000 x (Olympus CH-2)) as listed in tab. 1, and (wherever possible) used for identifying cyanobacteria and green algae to species level based on the following taxonomic references: Hibberd, 1981; Skinner & Entwisle, 2004; Anagnostidis & Komarek 2005; Komarek & Anagnostidis, 2005; Komarek & Komarkova-Legnerova, 2007; Alwathnani & Johansen, 2011; Hasler & *alii*, 2012; Vijayan & Ray, 2015; Kumar & *alii*, 2016. The mosses and lichens were studied in terms of morphology using a stereomicroscope (Olympus SZH10) and light microscopy (Olympus CH-2); mosses were identified by using taxonomic references (Smith, 2004; Rosentreter & *alii*, 2007); the lichen species were studied by the identification keys and in terms of their photobiont, and divided into two groups according to Temina & *alii* (2005), Rosentreter & *alii* (2007).

Statistical analyses

The differences in geomorphic and soil parameters among the three units were quantified using analysis of variance (ANOVA). Duncan's test was also applied post hoc to distinguish means for the different plot-directions at the three units of the alluvial fan. Statistical differences in BSCs community were detected with ANOVA followed by a Duncan's test. Data analysis was carried out with SPSS (ver. 20.0, IBM, US) software.

A multivariate statistical technique was performed to analyze significant relationships between geomorphic and soil factors with the composition of BSCs. Associations of soil physicochemical and geomorphic variables as explanatory variables with the assemblage of BSCs communities as response variables were investigated by using Canonical

TABLE 1 - Identified species of BSCs along studied alluvial fan. See also Figs S1-S4 in supplementary material.

Cyanobacteria	Green algae	Cyanolichen	Green algae lichen	Moss
Anabaena sp.	*Chlorella sp.*	*Collema crispum*	*Acarospora sp.*	*Bryum argenteum*
Aterocapsa cf. belizensis	*Chlorococcum infusionum*	*Collema occophorum*	*Aspicilia desertorum*	*Bryum caespiticium*
Gloeocapsa magma	*Cladophora sp.*	*Collema tenax*	*Candelariella citrina*	*Didymodon sp.*
Leptolyngbya boryana	*Eustigmatos polyphem*	*Collema sp.*	*Fulgensia fulens*	*Syntrichia caninervis*
Leptolyngbya cf. tenerrima	*Neochloris sp.*	*Leptogium sp.*	*Peltula sp.*	*Syntrichia ruralis*
Leptolyngbya sp.	*Oedogonium sp.*	*Peccania sp.*	*Psora cereriformis*	*Tortula inermis*
Microcoleus vaginatus	*Planktosphaeria sp.*		*Psora decipiens*	
Nostoc commune	*Pleurastrum sarcinoideum*		*psora sp.*	
Nostoc membranaceum	*Protococcus viridis*		*Squamarina lentigera*	
Oscillatoria annae	*Rhizoclonium riparium*		*Toninia sp*	
Oscillatoria irrigua	*Symbiochloris sp.*		.	
Oscillatoria splendida				
Oscillatoria tenuis				
Phormidium chalybeum				
Phormidium favosum				
Phormidium uncinatum				
Pseudanabaena sp.				
Tolypothrix sp.				

correspondence analysis (CCA) based on the Monte Carlo test in CANOCO v4.5 software. In order to analyze the geomorphic parameters, the mean dimensions of the length and width of clast were used; mean clast dimension; mean clast sorting, skewness, kurtosis. Median clast dimension and skewness were not included in the analysis due to high covariance with mean clast dimension.

RESULTS

Landform surfaces and BSCs cover

In general, BSC cover was relatively low over the entire alluvial fan area (total mean = 13.12%). However, a maximum of 18% cover was found on Unit 3. Cyanolichen and green algae lichen with a significant difference ($P < 0.05$) constitute the main cover of BSC in Unit 2 (fig. 2-5). In Unit 3, the dominant coverage of BSC consists of mosses with a significant difference ($P < 0.05$) (fig. 2-4,6). The lowest coverage of BSCs was in the Unit 1 ($P < 0.05$). The most coverage of BSC on the Unit 1 composed of cyanolichen and algae (tab. 2) (fig. 2-1,3).

The slope of the landform is between 3-8% and the elevation is between 1337-1380 m. On average, 47% of the land surface was covered by physical components, gravel and cobble cover were 39% for all the landform. Going forward to Unit 3, the geomorphic levels showed a decrease in the alignment and heterogeneous distribution of the clast surfaces, and skewness was towards the smaller surfaces, while Unit 1 showed negative and toward coarse surfaces. The kurtosis of the curve was wide in all us (tab. 3).

According to the Duncan's average comparison; the Unit 1 showed the highest elevation compared with other geomorphic levels. According to tab. 3 geomorphic parameters in this unit with a significant difference ($P < 0.05$) had slope, clast density and more physical components than other units and also had the highest level of bare soil. More than 50% of the surface of this unit is formed by gravel. An average of 50% of the size of the stone surface was 26.7 mm. The results of microtopography and mean in this unit were confirmed at smaller clast. It also has a moderate roughness level and a symmetrical distribution of clasts.

The Unit 2 of the geomorphological surface is at the interface between the highest and lowest elevations of geomorphic levels. Due to the structure of the debris flow in this unit, it has significantly higher cobble and microtopography than the Unit 1 ($P < 0.05$). On average, showed 50% stone size of 43.8 mm. The average of clast surfaces is approximately twice the size of the Unit 1, but it has a better sorting than other units. The results of the skewness curvature were confirmed toward the smaller clasts.

Unit 3 has the lowest elevation compared with other geomorphic levels. In this structure, there is a significant difference ($P < 0.05$) for lower gradient and also clast density, bare soil and lower physical cover than other units. Due to the location of the Unit 2 in the lower elevation, the clast sorting is undesirable. Also, the investigations showed the median clast dimension similar to those of Unit 3.

Soil physicochemical properties (tab. 4) in Unit 1, with significant difference ($P < 0.05$) showed high pH. The percentage of organic carbon, EC, phosphorus and potassium in this level is less than in other units. The results of soil samples in this unit confirms that the amount of sand and calcium carbonate is higher.

TABLE 2 - The distribution of BSC community types at different geomorphological units in the alluvial fan
Within a given coverage percentage biological soil crust community types, different superscripts (a, ab, b, c) indicate a significant difference among units (Mean ± Std. Deviation), respectively, at $p < 0.05$.

Cover (%)	Unit 1	Unit 2	Unit 3
ACC[1]	1.92 ± 1.08^a	2.01 ± 1.76^a	1.17 ± 0.71^a
CLC[2]	2.25 ± 1.6^b	5.83 ± 4.72^a	3.01 ± 1.75^b
GLC[3]	0.84 ± 0.73^b	3.51 ± 3.94^a	$1.75 \pm 1.05^{a,b}$
MC[4]	0.67 ± 1.36^c	4.34 ± 3.74^b	12.08 ± 10.41^a
Total BSC[5]	5.68 ± 2.92^b	15.67 ± 8.6^a	18.01 ± 13.33^a

[1] ACC = algae and cyanobacteria crust.
[2] CLC = cyanolichen crust.
[3] GLC = green algae lichen crust.
[4] MC = moss crust.
[5] BSC = biological soil crust community types.

TABLE 3 - The distribution of geomorphic parameters induced by different geomorphological units in the alluvial fan. Within a given geomorphic property, different superscripts (a, ab, b, c) indicate a significant difference among units (Mean ± Std. Deviation), respectively, at $p < 0.05$.

Parameters		Unit 1	Unit 2	Unit 3
Elevation (m)		1372.25 ± 3.51^a	1358.83 ± 6.39^b	1349.83 ± 5.98^c
Slope (%)		6.25 ± 0.86^a	4.91 ± 0.79^b	3.91 ± 1.16^c
Bare Soil (%)		9.91 ± 6.5^a	8.41 ± 7.35^a	6.33 ± 8.01^a
Gravel (%)		53.83 ± 17.5^a	23.58 ± 17.12^b	24.41 ± 15.26^b
Cobbles (%)		2.12 ± 4.24^b	8.66 ± 9.09^a	$3.91 \pm 4.22^{a,b}$
Physical Cover (%)		65.87 ± 16.16^a	40.66 ± 19.34^b	34.66 ± 19.99^b
Roughness Index		0.08 ± 0.05^b	0.14 ± 0.06^a	$0.11 \pm 0.06^{a,b}$
Clast Density		223.83 ± 70.03^a	129 ± 67.47^b	113.33 ± 58.88^b
Clast length	Mean (mm)	20.95 ± 14.1^b	45.52 ± 30.5^a	$30.18 \pm 13.36^{a,b}$
	Median (mm)	32.59 ± 40.22^a	61.15 ± 37.69^a	37.55 ± 23.74^a
	Sorting (ϕ)	0.95 ± 0.32^a	1.01 ± 0.31^a	1.09 ± 0.29^a
	Skewness	-0.069 ± 0.43^b	0.34 ± 0.49^a	$0.19 \pm .38^{a,b}$
	Kurtosis	0.82 ± 0.2^a	0.89 ± 0.3^a	0.75 ± 0.13^a
Clast width	Mean (mm)	13.55 ± 10.32^b	21.83 ± 14.13^a	$17.66 \pm 6.32^{a,b}$
	Median (mm)	$20.8 \pm 2\ 8.4^a$	26.51 ± 17.32^a	18.13 ± 8.02^a
	Sorting (ϕ)	1.07 ± 0.42^a	0.83 ± 0.21^a	0.99 ± 0.3^a
	Skewness	0.08 ± 0.39^a	0.07 ± 0.44^a	0.06 ± 0.32^a
	Kurtosis	0.8 ± 0.22^a	0.8 ± 0.37^a	0.69 ± 0.12^a

Unit 2 with a significant difference ($P < 0.05$) has lower soil pH, and has higher EC and potassium than the Unit 1. It also has higher sodium, calcium and magnesium contents than other units.

Unit 3 has moisture, silt, organic carbon ($P < 0.05$), high nitrogen and also with a significant difference ($P < 0.05$) lower soil pH, as well as sodium and calcium carbonate less than other units. In general, with the advancement toward Unit 3, soil moisture, organic carbon and phosphorus increased, and the amount of calcium carbonate and pH was reduced. Tab. 2 shows the distribution of soil characteristics along geomorphic surfaces of the alluvial fan.

Survey of BSCs habitat on the soil surface showed (fig. 3), algae biofilms, as well as lichens and in particular cyanobacteria, can protect soil particles. Extracellular polymeric substances secreted by algae and cyanobacteria kept soil particle together, increasing the stability of aggregates (fig. 3-6).

Generally, BSCs were more influenced by soil physicochemical parameters, while they were more affected morphologically in Unit 2. In Unit 3, BSCs were significantly affected by soil parameters.

The distribution of BSCs related to the heterogeneity of geomorphic parameters

According to the CCA analysis and based on the Monte Carlo test, BSCs parameters with respect to geomorphic variables are significant (F-ratio = 5.03, P-value = 0.001) and showed that the first two axes explain most of the variance (93.9%, tab. 5). As a result, these two axes were analyzed. According to tab. 5, along the first axis of landform, from the left to the right, toward Unit 1, the elevation and bare soil increased. In the second axis, there was a high correlation coefficient of geomorphic factors that increased from bottom to top, in the changes from Unit 1 to 3, the microtopography increased, and the slope and kurtosis reduced.

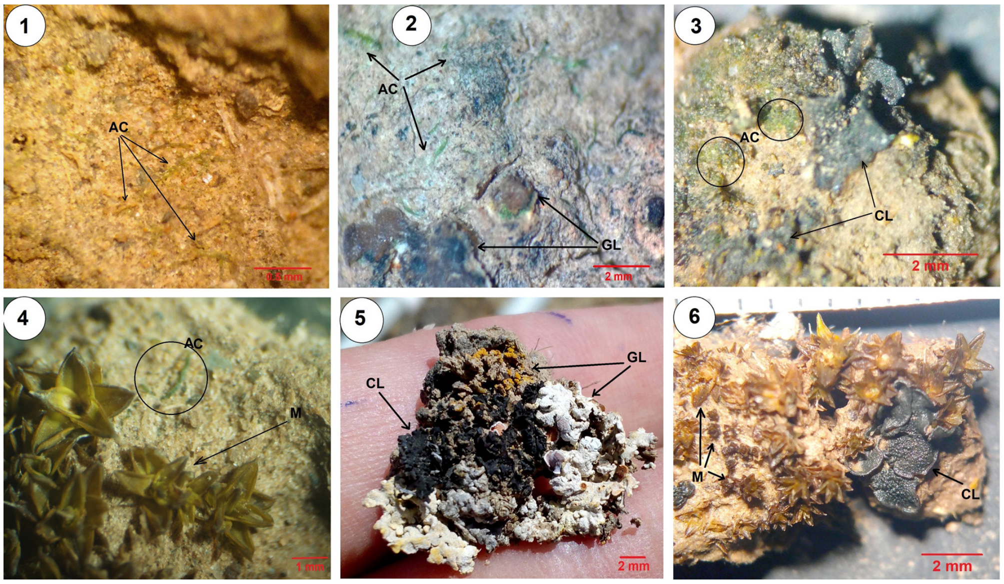

FIG. 2 - Images of various communities of BSCs: 1) Crust included: green algae and cyanobacteria species (AC), which was dominated in the unit 1. 2) Soil covered: green algae lichen species (GL) and AC, this crust dominated in the unit 2. 3) In this image BSCs consisted of: cyanolichen species (CL) and AC, they often found in the unit 1. 4) Crust included: moss species (M) and AC, which was dominated in the unit 3. 5) Soil covered: GL and CL, this crust found in the unit 2. 6) In this image BSCs consisted of: M and CL, this crust dominated in the unit 3.

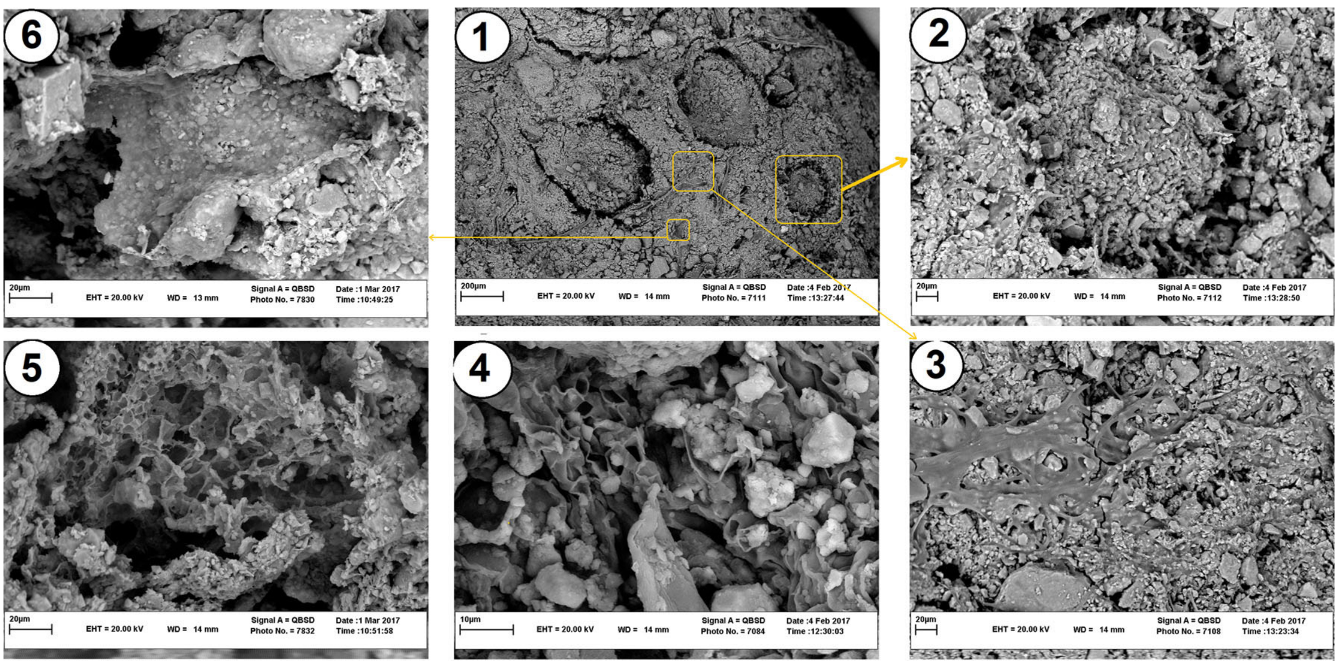

FIG. 3 - BSC explains by SEM images: 1) BSC consist: lichen, algae and cyanobacteria. 2) Terrestrial lichens show that fungi mycelium have been connected to soil. 3) Cyanobacteria crust protects soil particles. 4) The crust surface (lichen) shows as a place to absorb soil particles. 5) The biofilm of algae and cyanobacteria make porosity. 6) Image biofilm of algae and cyanobacteria that surrounded soil particles together.

According to fig. 4a, the mosses (MC) had the most direct correlation with the sorting, and an inverse relation with slope, gravel and elevation. Green algae lichen (GLC) were mostly affected by cobble, microtoprography and bare soil. Cyanolichen (CLC) was directly related to slope, gravel, kurtosis, and reduction of sorting. Cyanobacteria and green algae (ACC) had the highest correlation with slope and gravel. Tab. 5 shows the correlation coefficients of geomorphic variables for each unit.

The highest correlation coefficient was related to the change of units from top to bottom of the landform structure, elevation and bare soil (fig. 4). The rank correlation of BSCs was as follows:

From Unit 1 toward 3: MC > GLC > CLC > ACC
Elevation and bare soil: GLC > ACC > CLC > MC

The distribution of BSCs related to the heterogeneity of soil parameters

The results of CCA for BSCs were significant based on the Monte Carlo test (F-ratio = 4.714, P-value = 0.001) and showed the first two axes explain most of the vari-

TABLE 4 - The distribution of soil parameters induced by different geomorphological units in the alluvial fan. Within a given soil physicochemical properties, different superscripts (a, ab, b, c) indicate a significant among units (Mean ± Std. Deviation), respectively, at $p < 0.05$.

Parameters	Unit 1	Unit 2	Unit 3
Soil moisture (%)	1.83 ± 0.71^{b}	2.39 ± 0.47^{ab}	2.81 ± 0.87^{a}
Sand (%)	44.02 ± 3.22^{a}	43.19 ± 1.28^{ab}	41.37 ± 2.42^{b}
Silt (%)	33.37 ± 2.84^{b}	34.92 ± 2.28^{ab}	37.16 ± 4.17^{a}
Clay (%)	22.61 ± 2.56^{a}	21.89 ± 1.56^{a}	21.46 ± 2.4^{a}
SOC (%)	0.33 ± 0.12^{c}	0.51 ± 0.15^{b}	0.63 ± 0.08^{a}
$CaCO_3$ (%)	21.37 ± 2.39^{a}	20.92 ± 1.01^{a}	20.68 ± 1.32^{a}
pH	8.36 ± 0.13^{a}	8.17 ± 0.04^{b}	8.14 ± 0.04^{b}
EC (ds/m)	0.26 ± 0.02^{b}	0.36 ± 0.07^{a}	0.33 ± 0.08^{a}
N (mg/kg)	679.68 ± 251.84^{b}	$809.01 \pm 103.89^{a,b}$	947.19 ± 175.15^{a}
P (mg/kg)	34.19 ± 8.47^{b}	41.17 ± 6.21^{a}	43.67 ± 7.45^{a}
K (mg/kg)	207.45 ± 20.95^{b}	337.11 ± 80.18^{a}	300.89 ± 145.6^{a}
Na (mg/kg)	$61.81 \pm 9.15^{a,b}$	65.38 ± 6.22^{a}	57.87 ± 5.76^{b}
Ca (mg/kg)	403.28 ± 34.37^{b}	439.04 ± 33.8^{a}	$410.71 \pm 49.3^{a,b}$
Mg (mg/kg)	24.33 ± 15.53^{b}	44.15 ± 21.79^{a}	25.54 ± 6.73^{b}

ance (89.1%, tab. 6). According to tab. 6, along the first axis, from left to right toward Unit 1 sodium increased, while soil moisture and nitrogen levels decreased. In the second axis, there was a high correlation coefficient between soil parameters such as nitrogen and sodium, nitrogen increasing from bottom to top and sodium content decreasing.

According to fig. 4b, the mosses (MC) had the highest direct correlation with soil moisture, organic carbon and phosphorus, and an inverse relationship with sodium, calcium carbonate and sand content. Green algae lichen (GLC) was influenced more by calcium and pH variables. Cyanolichen (CLC) had the most direct correlation with calcium carbonate, sodium, sand and Unit 1. Cyanobacteria and green algae (ACC) had the highest correlation with the amount of magnesium, sand, and sodium, and in the second rank correlated with pH, and also in relation to changes in units, had the least effect on other species. Tab. 6 shows the correlation coefficients of geomorphic variables for each units.

In this analysis, the highest correlation coefficient was related to the change of units from top to bottom of the landform and soil moisture. That the rank correlation is BSCs as follows:

From Unit 1 toward 3: MC > GLC > CLC > ACC

Soil moisture: MC > CLC > ACC > GLC

DISCUSSION

Landforms are associated with a distinct set of biotic and abiotic properties of the Earth's surface. In general, landforms are dominated by abiotic components with limited distribution of biological components (Johansen & *alii*, 2001; Belnap & *alii*, 2007; Pietrasiak & *alii*, 2011a, b; Concostrina-Zubiri & *alii*, 2018). This study identifies the abiotic properties of the landform surfaces in an arid ecosystem of Iran, which determine the components of BSCs communities. BSCs dominated in the area, including cyanolichen and moss.

The geomorphic effects on BSC distribution in different units

As a result of the debris flow-dominated nature of the alluvial fan studied, there are many stone surfaces. Unit 1, due to low microtoprography, gravel percent and slope were high, has a relatively smooth surface with low coverage of BSCs, thus lower permeability and runoff probability was higher. In contrast, Unit 3 has slopes and lower clast levels, higher microtoprography, and also a lot of BSCs, thus increasing permeability and decreasing runoff. These findings confirm the researches of Herrick & *alii* (2010), Williams & *alii* (2013) and Pietrasiak & *alii* (2014).

Sediments and dust can accumulate on any object that encounters by the motion of wind. Consequently, in small areas, sedimentation accumulated between the cracks of clasts, as well as gaps and roughness of the surface of the various BSCs, or lichens and mosses thalli (Belnap, 2006; Hirmas & Graham, 2011). In a wider space, topography and moisture promote sediment accumulation. The clast surfaces with a smooth topography in desert pavement, accumulated the less dust (Hirmas & *alii*, 2011). According to the microtopography and BSCs of the alluvial fan, the capability of units to accumulate sediment and dust is as follows: Unit 1 < Unit 2 < Unit 3. While the bare soil (about 10%) has the largest amount at the Unit 1. This confirms the results of Pietrasiak & *alii* (2014); their research showed that the roughness index regarding microtopography affected by crusts increases capturing sediment and dust on the surface of a landform.

TABLE 5 - The correlation coefficients between geomorphic variables and CCA axis, and also the results of CCA.

Geomorphic variables	Unit 1		Unit 2		Unit 3		Landform	
	ENVI AX1	ENVI AX2	ENVI AX1	ENVI AX2	ENVI AX1	ENVI AX2	ENVI AX1	ENVI AX2
Elevation	-0.3598	0.2325	0.6416	0.3481	-0.1472	-0.1933	0.7427	-0.1011
Slope	0.053	0.6336	-0.5352	-0.0788	0.0954	0.2691	0.3872	-0.4425
Bare Soil	0.1397	0.1831	0.6375	0.5028	0.525	0.1636	0.6728	0.2229
Gravel	-0.8988	-0.0248	-0.1263	0.1506	0.303	0.1901	0.2782	-0.3176
Cobble	-0.2977	-0.2437	0.5371	0.5379	-0.0352	0.4543	0.4768	0.651
RI	0.1377	0.5352	0.6455	0.1905	0.1437	0.2683	0.3581	0.4917
Clast Density	-0.9157	-0.0512	0.2254	0.4715	0.3011	0.288	0.4854	-0.0499
Clast Dimension	0.0878	0.1896	-0.204	-0.0726	-0.2386	0.3136	-0.0676	0.0046
Clast Sorting	-0.0711	0.2857	-0.1291	0.6801	-0.0567	0.1496	-0.15	0.3147
Clast Kurtosis	0.0053	-0.3888	-0.4975	-0.21	0.0732	0.0476	-0.0555	-0.5073
Along	_	_	_	_	_	_	-0.7866	0.5273
Eigenvalues	0.277	0.127	0.429	0.178	0.113	0.063	0.335	0.116
Species-geomorphic correlations								
	0.973	0.983	0.974	0.991	0.849	0.895	0.881	0.783
Cumulative percentage variance of species-geomorphic relation								
	59.6	87.1	68.3	96.5	55	85.6	69.7	93.9
F_ratio	3.736		4.967		0.54		5.03	
P_value	0.025		0.045		0.799		0.001	

TABLE 6 - The correlation coefficients between soil variables and CCA axis, and also the results of CCA.

Soil variables	Unit 1		Unit 2		Unit 3		Landform	
	ENVI AX1	ENVI AX2	ENVI AX1	ENVI AX2	ENVI AX1	ENVI AX2	ENVI AX1	ENVI AX2
Moisture	-0.4742	-0.685	-0.0741	-0.326	-0.4934	-0.3219	-0.5673	-0.0788
Sand	-0.5321	-0.25	-0.0984	0.228	0.1804	-0.0421	0.4555	-0.2787
Silt	-0.3571	0.1236	0.5498	-0.5031	0.0873	0.1909	-0.0836	0.2718
Clay	0.9686	0.1761	-0.7194	0.5555	-0.3004	-0.2801	-0.3592	-0.1275
SOC	0.3428	-0.6281	0.4814	-0.6267	-0.167	0.0531	-0.3503	0.0673
CaCO3	0.7135	-0.5026	-0.1886	0.3582	0.3991	0.609	0.3222	-0.2737
pH	0.3626	0.5428	0.293	0.3914	0.0205	-0.1179	0.4023	0.0327
EC	-0.6858	0.4297	-0.5334	0.4978	0.8174	0.174	-0.032	0.1643
Na	-0.5491	-0.0913	0.0499	-0.5557	0.2789	0.2004	0.5574	-0.3766
Ca	0.3731	0.4152	-0.5861	0.6883	0.4124	0.276	0.1746	0.2064
Mg	0.9136	0.0558	0.5179	-0.6547	-0.5444	0.0957	0.3966	-0.136
N	0.5387	0.5178	0.6739	-0.389	-0.3599	-0.338	-0.5194	0.4379
P	-0.6812	-0.3218	0.0902	-0.571	-0.673	-0.0015	-0.3831	-0.0683
K	0.6667	0.4152	-0.5549	0.149	0.0835	0.2353	-0.0375	0.1317
Along	_	_	_	_	_	_	-0.7598	0.3075
Eigenvalues	0.258	0.125	0.442	0.18	0.168	0.077	0.394	0.092
Species-geomorphic correlations								
	0.94	0.974	0.988	0.997	1	1	0.957	0.711
Cumulative percentage variance of species-geomorphic relation								
	59.2	87.7	68.8	96.8	57.9	84.6	72.2	89.1
F_ratio	6.632		9.984		271.006		4.714	
P_value	0.001		0.048		0.001		0.001	

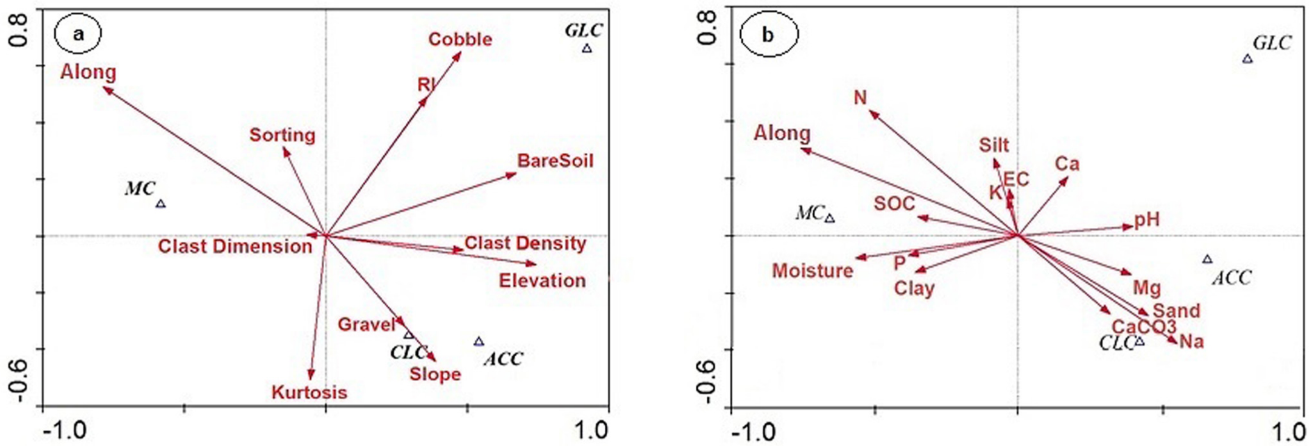

FIG. 4 - CCA biplot for (a) biological soil crust communities (ACC=algae and cyanobacteria crust, CLC=cyanolichen crust, GLC =green algae lichen crust, MC =moss crust) and measured geomorphic variables, (b) biological soil crust communities and measured soil variables.

In smaller space, microbial communities associated with BSCs can affect the flow of water and wind (Eldridge & Greene, 1994; Eldridge & *alii*, 2002; Belnap & *alii*, 2002). In particular, clasts and BSCs protect the soil surface and the underlying soil from surface erosion (Descroix & *alii*, 2001; Neave & Abrahams, 2001; Belnap, 2006; Herrick & *alii*, 2010), and especially sheet erosion is reduced (Valentin & Casenave, 1992). Also, BSCs cause soil aggregation and porosity (fig. 3-5) (Neave & Abrahams, 2001; Belnap, 2006; Wainwright, 2009; Sepehr & *alii*, 2018).

Algae crust grows inside the soil and parts of the Earth's surface, where exposed to the effects of rainfall (Belnap, 2006). Unit 1 has a high erosion potential. In contrast to the soil covered with lichen and moss, algae crusts that protected of soil surface and the raindrops infiltrated into soil. Unit 3 is the less exposed to erosion. These results confirm the findings of Belnap (2006) in relation to the effects of BSCs on hydrology.

The most important management factors for green algae, cyanobacteria and cyanolichen were variables that determined micro-habitats: elevation and gravel keep water and around them, and are characteristics in Unit 1. The abundance of crusts of lichens and mosses can be related to the clast cobbles, bare soil and microtopeography of the habitat (fig. 5). In addition, microtopography that has been created by the stone surfaces can attract dust, water retention capacity, and improved nutrition of lichens (Belnap, 2002, Lalley & Viles, 2006), thus lichens are the main cover of the BSCs in Unit 2. These results confirm findings of Pietrasiak & *alii* (2014 and 2011a, b) and Williams & *alii* (2013); they found that micro-habitats are being created in gaps and crack of large stone surfaces for the presence of BSCs.

As seen in the CCA biplot diagram (fig. 4), the Unit 1 is associated with communities that are predominantly composed of cyanolichen, algae and cyanobacteria. This flow can be correlated with the reduction of microtopography and clast density increased during units changes along the alluvial fan. These micro-habitats have less desirability for lichens and mosses, because they provide less space for them. On the other hand, the Unit 1 is an obstacle to the presence of BSCs, by increasing clast density, sorting is undesirable, and the skewness go towards smaller surfaces with a widespread distribution.

Relationships between BSCs and soil properties in different units

Geomorphology strongly affects the allocation of soil resources. BSCs distributed on debris alluvial fan involve a complex assemblage regarding two or three combinations of cyanobacteria, algae, lichen, and moss. Results indicated that dynamics of BSCs are significantly governed by geomorphic surfaces from the apex of an alluvial fan towards the base surfaces, which depend on deposition dynamics and soil properties. Deposits of apex and top points showed generally coarser texture and poorer sorting and roundness, also deposits were increased from top towards base points, and was found a large amount of fine sediment on the base surfaces. This sorting and roundness status led to better water drainage ratio from the highlands to the lowlands and thus increasing the mosses and lichens in BSCs. These results confirm the studies of Li & *alii* (2002) and Bowker (2007) in the indirect effect of geomorphology on the pattern of biodiversity distribution among the species of BSCs, causing that cyanobacteria and algae often occurred in the first stages of the sequence of BSCs, and then the lichens, and finally the mosses gradually appeared in the later stages (Bashtian & *alii*, 2019). Water is a dominant factor in the efficiency of desert structure in biodiversity (Whitford, 2002). The higher soil moisture content, the moss development is facilitated instead of cyanobacteria and lichen (Li & *alii*, 2002).

In other words, from Unit 1 to Unit 3, the distribution pattern of BSCs in primary sequences is related to cyanobacteria, algae, and cyanolichen, and for the final sequence is regarded to lichens and mosses. Fig. 5 shows a schematic picture of BSCs pattern dynamics along alluvial fan regarding deposition and morphology changes. Soil texture indicates the relative frequency of sand, silt, and clay, that could affect soil moisture conditions. Kleiner & Harper (1977) found that silt loam soils hold the most different populations of cyanobacteria, lichens, and mosses as compared to sandy and clay textures. Thus, results showed that soil texture could affect specie composition of BSCs. The soil texture in this study site generally belongs to the class loam. There is more silt in the soil, which thus increased the coverage of BSCs.

According to tabs 2 and 4, the soil pH decreases from Unit 1 to Unit 3. As a result, the dominant species constituting Unit 1 were cyanobacteria, algae, and cyanolichen; and the dominant species of Unit 3 are mosses. Also an ecological succession can be considered for this evolution. Chamizo & *alii* (2012) and Miralles & *alii* (2012) found that the soil pH decreases with the development of BSCs (from primary sequences such as cyanobacteria to the final sequence, such as mosses and lichens).

BSCs play an important role in the production of SOC by carbon fixation (Beymer & Klopatek, 1991) and decomposition of organic matter (Dainin & Ganor, 1991) in arid soils. Unit 3 have more organic carbon compared to the other units and there is an inverse relationship between SOC and soil pH, also increasing carbon fixation in the presence of lichens and mosses. In the studied alluvial fan, the base surface shows high SOC involving Unit 3, and moss species are dominant BSCs. These results confirm the studies of Phillips & Belnap (1998), who argued that carbon stabilization increases in the presence of lichens and mosses.

The amount of nitrogen in the soil of Unit 3 with mosses and lichens, was almost 1.5 times higher than that in the territory of Unit 1. These results are in accordance with the findings of numerous studies, which showed that the existence of BSCs increases soil nitrogen even up to 200% (Defalco, 1995), and they convert atmospheric nitrogen into a form usable for plants (Belnap, 2003).

In Unit 2, magnesium, calcium, sodium and potassium content increased significantly with other units, which confirmed the results of Williams (1994), showing that some elements increase in the soil due to the presence of BSCs. The elements such as copper, magnesium, calcium, sodium, potassium and zinc stick to the outer surface of the cell wall of lichens. When lichens dry, wet placed, the elements are washed from the lichen wall and added into the soil, and because of their positive load, they are absorbed by negative colloids, thus their amount increases in such soil.

CONCLUSIONS

In general, the components of the landscape in arid and semi-arid regions provide a unique opportunity to understand the processes and interaction between abiotic and biotic components. In this research, the relationships

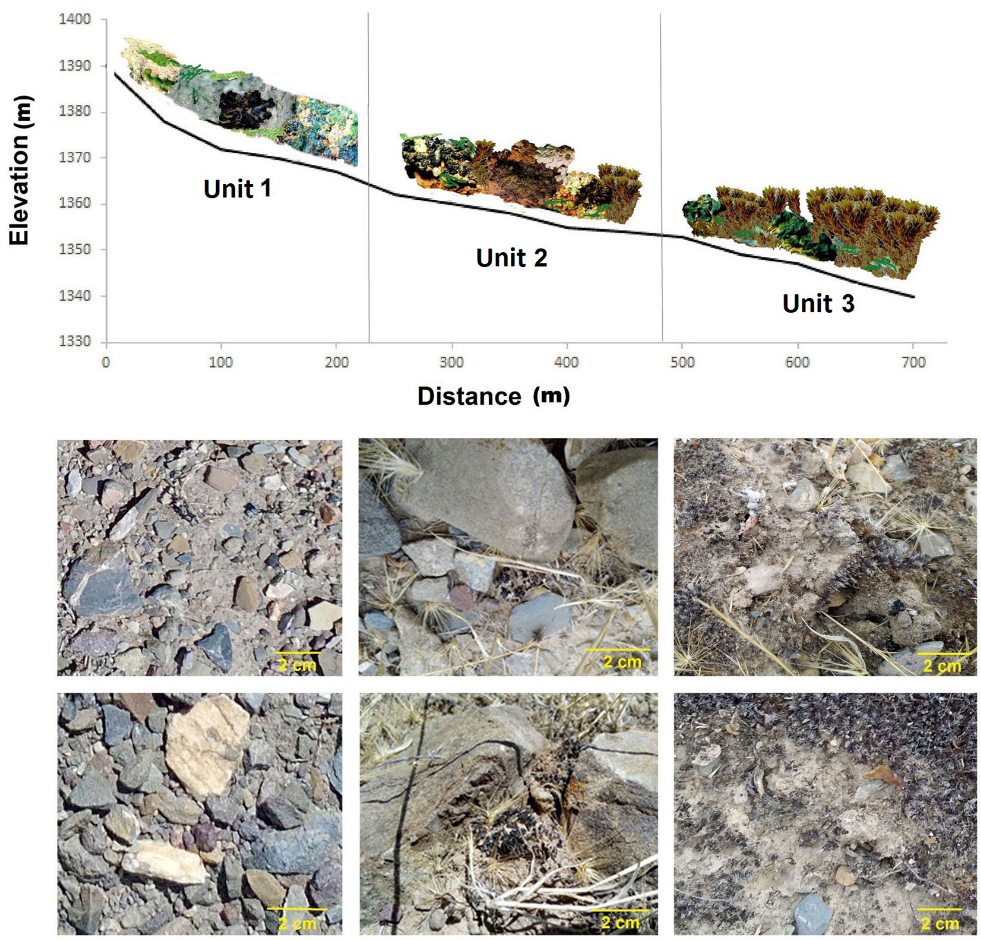

FIG. 5 - The trend micro-habitations and BSCs of variation, regarding deposition morphology changes in along gradient of the study area. Unit 1, including: green algae, cyanobacteria and cyanolichen of BSCs, and sediments are in size of gravel. In unit 2, cyanolichen and green algae lichen constitute the main cover of BSC, and sediments often are cobbles. In unit 3, the dominant coverage of BSC is moss, and have lowest physical cover.

between the distribution of BSCs, the geomorphologic characteristics and physicochemical properties of soils were investigated along the morphology of alluvial fan in a dry area of Iran. In the most elevated units with high clast density, especially gravel, lighter soil texture and higher pH, soil levels are dominated by the primary sequences of cyanobacteria, green algae and cyanolichen; the pavement surface in Unit 1 prevents the formation of BSCs. Due to the structure of the alluvial fan debris flow, in Unit 2 micro-habitats, resulting from gaps and spaces between the cobble clasts that maintain sediments and improve nutrients, conditions for subsequent sequences of BSCs, especially lichens are created. While decreasing the slope and increasing the microtopeography, the amount of silt and loamy soil leads to more moisture content in Unit 3. As a result, the development of moss and lichen in subsequent sequences is promoted. Going forward to Unit 3, the biodiversity of BSCs is reduced. The environmental functions of BSCs, such as the stabilization of nitrogen and carbon by cyanobacteria and algae, are less than by mosses and lichens. As it progresses along the landform, in the lower elevation erosion is reduced and soil fertility increased. The results showed that micro-geomorphology determines the distribution of BSCs which is mainly related to soil characteristics.

REFERENCES

Allmaras R.R., Burwell R.E., Larson W.E. & Holt R.F. (1966) - *Total porosity and random roughness of inter row zone as influenced by tillage.* USDA Conserv. Res. Rep. 7. U.S. Gov. Print Office, Washington DC.

Alwathnani H. & Johansen J.R. (2011) - *Cyanobacteria in soils from a Mojave Desert ecosystem.* Monographs of the Western North American Naturalist, 5, 71-89.

Anagnostidis K. & Komarek J. (2005) - *Cyanoprokariota.* Teil 2: Oscillatoriales, Gustav Fischer Verlag, Berlin.

Bashtian M.H., Sepehr A., Farzam M. & Bahreini M. (2019) - *Biological soil crusts, plant functional groups, and soil parameters in arid areas of Iran.* Polish Journal of Ecology, 66, 337-351.

Belnap J. & Gillette D.A. (1998) - *Vulnerability of desert biological soil crusts to wind erosion: the influences of crust development, soil texture, and disturbance.* Journal of Arid Environments, 39 (2), 133-142.

Belnap J. & Lange O.L. (2003) - *Biological soil crusts: characteristics and distribution*. In: Belnap J. & Lange O. (Eds.), Biological soil crusts: structure, function, and management, 150, Springer, 506 pp.

Belnap J, Phillips S.L, Herrick J. & Johansen J. (2007) - *Wind erodibility of soils at Fort Irwin, California (Mojave Desert), USA, before and after trampling disturbance: implications for land management.* Earth Surface Processes and Landforms, 32 (1), 75-84.

Belnap J. & Gardner J.S. (1993) - *Soil microstructure in soils of the Colorado Plateau: the role of the cyanobacterium Microcoleus vaginatus.* The Great Basin Naturalist, 40-47.

Belnap J. (1994) - *Potential role of cryptobiotic soil crust in semiarid rangelands.* Proceedings- Ecology and Management of Annual Rangelands, 179-185.

Belnap J. (2002) - *Impacts of off-road vehicles on nitrogen cycles in biological soil crusts: resistance in different US deserts.* Journal of Arid Environments, 52 (2), 155-165.

Belnap J. (2003) - *Factors influencing nitrogen fixation and nitrogen release in biological soil crusts.* In: Belnap J. & Lange O. (Eds.), Biological soil crusts: structure, function, and management, 150, Springer, 506 pp.

Belnap J. (2006) - *The potential roles of biological soil crusts in dryland hydrologic cycles.* Hydrological Processes, 20 (15), 3159-3178.

Black C.A. (1965) - *Methods of soil analysis: part I. Physical and mineralogical properties.* American Society of Agronomy, Madison, Wisconsin, USA.

Bouyoucos G.J. (1962) - Hydrometer method improved for making particle size analyses of soils. *Agronomy Journal*, 54 (5), 464-465.

Bowker M.A., Belnap J., Budel B., Sannier C., Pietrasiak N., Eldridge D.J. & Rivera-Aguilar V. (2016) - *Controls on distribution patterns of biological soil crusts at micro- to global scales.* In: Weber B. Budel B & Belnap J. (Eds.), Biological Soil Crusts: an Organizing Principle in Drylands. *Springer, Switzerland*, 226, 549 pp.

Bowker M.A. & Belnap J. (2008) - *A simple classification of soil types as habitats of biological soil crusts on the Colorado Plateau, USA.* Journal of Vegetation Science, 19, 831-840.

Bowker M.A. (2007) - *Biological soil crust rehabilitation in theory and practice: an underexploited opportunity.* Restoration Ecology, 15 (1), 13-23.

Bremner J.M. & Mulvaney C.S. (1982) - *Methods of soil analysis, part 2. Chemical and microbiological properties.* American Society of Agronomy, 595-624, Madison, Wisconsin, USA.

Bu C., Wu S., Zhang K., Yang Y. & Gao G. (2013) - *Biological soil crusts: an eco-adaptive biological conservative mechanism and implications for ecological restoration*. Plant Biosyst, 149, 364-373.

Bu C., Zhang P., Wang C., Yang Y., Shao H.B. & Wu S. (2016) - *Spatial distribution of biological soil crusts on the slope of the Chinese Loess Plateau based on canonical correspondence analysis.* Catena, 137, 373-381.

Budel B., Darienko T., Deutschewitz K., Dojani S., Friedl T., Mohr K I., Salisch M., Reisser W. & Weber B. (2009) - *Southern African biological soil crusts are ubiquitous and highly diverse in drylands, being restricted by rainfall frequency.* Microbial Ecology 57, 229-247.

Chamizo S., Cantón Y., Miralles I. & Domingo F. (2012) - *Biological soil crust development affects physicochemical characteristics of soil surface in semiarid ecosystems.* Soil Biology and Biochemistry, 49, 96-105.

Chen Y., Wang Q., Li W. & Ruan X. (2007) - *Microbiotic crusts and their interrelations with environmental factors in the Gurbantonggut desert, western China.* Environmental Geology, 52 (4), 691-700.

Concostrina-Zubiri L., Martínez I. & Escudero A. (2018) - *Lichen-biocrust diversity in a fragmented dryland: Fine scale factors are better predictors than landscape structure.* Science of the Total Environment, 628, 882-892.

Cornelissen J.H., Lang S.I., Soudzilovskaia N.A. & During H.J. (2007) - *Comparative cryptogam ecology: a review of bryophyte and lichen traits that drive biogeochemistry.* Annals of Botany, 99 (5), 987-1001.

Csotonyi J.T. & Addicott J.F. (2004) - *Influence of trampling-induced microtopography on growth of the soil crust bryophyte Ceratodon purpureus in Jasper National Park.* Canadian Journal of Botany, 82 (9), 1382-1392.

Danin A. & Ganor E. (1991) - *Trapping of airborne dust by mosses in the Negev Desert, Israel.* Earth Surface Processes and Landforms, 16 (2), 153-162.

Davidson D.W, Bowker M., George D., Phillips S.L. & Belnap J. (2002) - *Treatment effects on performance of N-FIXING lichens in disturbed soil crusts of the Colorado Plateau.* Ecological Applications, 12 (5), 1391-1405.

DEFALCO L.A. (1995) - *Influence of cryptobiotic soil crusts on winter annuals and foraging movements of the desert tortoise.* Department of Biology. Colorado State University, Fort Collins, Co. USA.

DEGÓRSKI M. (2003) - *Pedodiversity as a part of geodiversity in creation of landscape structure. Multifunctional Landscape.* Monitoring Diversity and Management, WIT PRESS, Southampton, Boston, 2, 105-121.

DESCROIX L,. VIRAMONTES D., VAUCLIN M., BARRIOS J.G. & ESTEVES M. (2001) - *Influence of soil surface features and vegetation on runoff and erosion in the Western Sierra Madre (Durango, Northwest Mexico).* Catena, 43 (2), 115-135.

ELDRIDGE D.J. (1999) - *Distribution and floristics of moss- and lichendominated soil crusts in a patterned Callitris glaucophylla woodland in eastern Australia.* Acta Oecol, 20, 159-170.

ELDRIDGE D. & GREENE R. (1994) - *Assessment of sediment yield by splash erosion on a semi-arid soil with varying cryptogam cover.* Journal of Arid Environments, 26 (3), 221-232.

ELDRIDGE D.J., ZAADY E. & SHACHAK M. (2002) - *Microphytic crusts, shrub patches and water harvesting in the Negev Desert: the Shikim system.* Landscape Ecology, 17 (6), 587-597.

EVANS R.D. & JOHANSEN J.R. (1999) - *Microbiotic crusts and ecosystem processes. Critical Review in Plant Sciences,* 18, 183-225.

EVANS R.D. & BELNAP J. (1999) - *Long-term consequences of disturbance on nitrogen dynamics in an arid ecosystem.* Ecology, 80, 150-160.

FOLK RL. (1980) - *Petrology of sedimentary rocks.* Hemphill Publishing Company, Austin, USA, 184 pp.

FRIEDMANN E.I. & GALUN M. (1974) - *Desert algae, lichens and fungi.* In: BROWN G.W. (Ed.), Desert Biology. Academic Press, New York, 165-212.

GEORGE D.B., DAVIDSON D.W., SCHLIEP K.C. & PATRELLKIM L.J. (2000) - *Microtopography of microbiotic crusts on the Colorado Plateau, and distribution of component organisms.* Western North American Naturalist, 60, 343-354.

GOUDIE A.S. & MIDDLETON N.J. (2006) - *Desert dust in the global system.* Springer, Berlin, 288 pp.

HASLER P., DVORAK P., JOHANSEN J.R., KITNER M., ONDREJ V. & POULÍCKOVA A. (2012) - *Morphological and molecular study of epipelic filamentous genera Phormidium, Microcoleus and Geitlerinema (Oscillatoriales, Cyanophyta/Cyanobacteria).* Fottea, 12, 341-356.

HERRICK J., VAN ZEE J., BELNAP J., JOHANSEN J. & REMMENGA M. (2010) - *Fine gravel controls hydrologic and erodibility responses to trampling disturbance for coarse-textured soils with weak cyanobacterial crusts.* Catena, 83 (2), 119-126.

HIBBERD D.J. (1981) - *Notes on the taxonomy and nomenclature of the algal classes Eustigmatophyceae and Tribophyceae (synonym Xanthophyceae).* Botanical Journal of the Linnean Society, 82, 93-119.

HIRMAS D.R., GRAHAM R.C. & KENDRICK KJ. (2011) - *Soil-geomorphic significance of land surface characteristics in an arid mountain range, Mojave Desert, USA.* Catena, 87 (3), 408-420.

HIRMAS D.R. & GRAHAM R.C. (2011) - *Pedogenesis and soil-geomorphic relationships in an arid mountain range, Mojave Desert, California.* Soil Science Society of America Journal, 75 (1), 192.

JOHANSEN J.R, BRITTON C., ROSATI T.C., LI X., ST CLAIR L.L., WEBB B.L., KENNEDY A.J. & YANKO K.S. (2001) - *Microbiotic crust of the Mojave Desert: factors influencing distribution and abundance.* In: ELSTER J., SECKBACH J., VINCENT W.F., LHOTSKÝ O. (Eds.), Algae and extreme environments. Proceeding International Conference, Třeboň, Nova Hedwigia, Beiheft, 123, 341-371.

KIDRON G.J., VONSHAK A. & ABELIOVICH A. (2009) - *Microbiotic crusts as biomarkers for surface stability and wetness duration in the Negev Desert.* Earth Surface Processes and Landforms, 34, 1594-1604.

KLEINER E.F. & HARPER K. (1977) - *Soil properties in relation to cryptogamic groundcover in Canyonlands National Park.* Rangeland Ecology and Management/Journal of Range Management Archives, 30 (3), 202-205.

KNUDSEN D., PETERSON G.A. & PRATT P.F. (1982) - *Lithium, sodium and potassium.* In: PAGE A.L., MILLER R.H. & KEENEY D.R. (Eds.), Methods of Soil Analysis Part 2: Chemical and Microbiological Properties. American Society of Agronomy, Madison, Wisconsin, 225-246.

KOMAREK J. & ANAGNOSTIDIS K. (2005) - *Cyanoprokaryota, 2. Teil: Oscillatoriales.* In: BUDEL B., GARTNER G., KRIENITZ L., & SCHAGERL M., Süßwasserflora von Mitteleuropa. Elsevier GmbH, Munchen, 19/2, 759 pp.

KOMAREK J. & KOMARKOVA–LEGNEROVA J. (2007) - *Taxonomic evalution of the cyanobacterial microflora from alkaline marshes of northern Belize. 1. Phenotypic diversity of coccoid morphotypes.* New Hedwigia, 84, 65-111.

KUMAR D., KAŠTÁNEK P. & ADHIKARY S. (2016) - *Diversity of cyanobacteria in biological crusts on arid soils in the Eastern region of India and their molecular phylogeny.* Research Communications, Current Science, 110 (10), 1999-2004.

KUTIEL P., LAVEE H. & ACKERMANN O. (1998) - *Spatial distribution of soil surface coverage on north and south facing hillslopes along a Mediterranean to extreme arid climatic gradient.* Geomorphology, 23, 245-256.

LAITY J.J. (2006) - *Deserts and desert environments.* Wiley-Blackwell, 360 pp.

LALLEY J. & VILES H. (2006) - *Do vehicle track disturbances affect the productivity of soil-growing lichens in a fog desert?* Functional Ecology, 20 (3), 548-556.

LI X.R., HE M.Z., ZERBE S., LI X.J. & LIU L.C. (2010) – *Micro-geomorphology determines community structure of biological soil crusts at small scales.* Earth Surface Processes and Landforms, 35 (8), 932-940.

LI X.R., JIA X.H., LONG L.Q. & ZERBE S. (2005) - *Effects of biological soil crusts on seed bank, germination and establishment of two annual plant species in the Tengger Desert (N China).* Plant and Soil, 277 (1), 375-385.

LI X.R., WANG X.P., LI T. & ZHANG JG. (2002) - *Microbiotic soil crust and its effect on vegetation and habitat on artificially stabilized desert dunes in Tengger Desert, North China.* Biology and Fertility of Soils, 35 (3), 147-154.

LONGTON R.E. (1997) - *The role of bryophytes and lichens in polar ecosystems.* Special Publication-British Ecological Society, 13, 69-96.

MCKENNA NEUMAN C., MAXWELL C.D. & BOULTON J.W. (1996) - *Wind transport of sand surfaces crusted with photoautotrophic microorganisms.* Catena, 27, 229-247.

MIRALLES I., TRASAR-CEPEDA C., LEIRÓS M.C. & GIL-SOTRES F. (2012) - *Labile carbon in biological soil crusts in the Tabernas desert, SE Spain.* Soil Biology and Biochemistry, 58, 1-8.

NEAVE M., ABRAHAMS A.D. (2001) - *Impact of small mammal disturbances on sediment yield from grassland and shrubland ecosystems in the Chihuahuan Desert.* Catena, 44 (4), 285-303.

NELSON D.W. & SOMMERS L.E. (1982) - *Total carbon, organic carbon and organic matter. In Methods of Soil Analysis Part 2: Chemical and Microbiological Properties.* PAGE A.L., MILLER R.H. & KEENEY D.R. (Eds.). American Society of Agronomy, Madison, Wisconsin, 539-a577.

NIU J., YANG K., TANG Z. & WANG Y. (2017) - *Relationships between Soil Crust Development and Soil Properties in the Desert Region of North China.* Sustainability, 9 (5), 725.

OLSENARD S.R. & SOMMERS L.E. (1982) - *Phosphorus.* In: PAGE A.L., MILLER R.H. & KEENEY D.R. (Eds.), Methods of Soil Analysis Part 2: Chemical and Microbiological Properties. American Society of Agronomy, Madison, Wisconsin, 403-430.

PHILLIPS S.L. & BELNAP J. (1998) - *Shifting carbon dynamics due to the effects of Bromus tectorum invasion on biological soil crusts.* Ecological Bulletin, 79, 205.

PIETRASIAK N., DRENOVSKY R.E., SANTIAG L.S. & GRAHAM R.C. (2014) - *Biogeomorphology of a Mojave Desert landscape—Configurations and feedbacks of abiotic and biotic land surfaces during landform evolution.* Geomorphology, 206, 23-36.

PIETRASIAK N., JOHANSEN J.R. & DRENOVSKY R.E. (2011a) - *Geologic composition influences distribution of microbiotic crusts in the Mojave and Colorado Deserts at the regional scale.* Soil Biology and Biochemistry, 43 (5), 967-974.

PIETRASIAK N., JOHANSEN J.R., LADOUX T. & GRAHAM R.C. (2011b) - *Comparison of disturbance impacts to and spatial distribution of biological soil crusts in the Little San Bernardino Mountains of Joshua Tree National Park, California.* Western North American Naturalist, 71 (4), 539-552.

PIETRASIAK N., REGUS J.U., JOHANSEN J.R., LAM D. & SACHS J.L. (2013) - *Biological soil crust community types differ in key ecological functions.* Soil Biology and Biochemistry, 65, 168-171.

RIETKERK M., DEKKER S.C., RUITER P.C. & VAN DE KOPPEL J. (2004) - *Self-organized patchiness and catastrophic shifts in ecosystems*. Science, 305 (5692), 1926-1929.

ROSENTRETER R.M., BOWKER M. & BELNAP. J. (2007) - *A Field Guide to Biological Soil Crusts of Western U.S. Drylands.* U.S. Government Printing Office, Denver, Colorado. 118.

SEITZ S. NEBEL M. GOEBES P. KAPPELER K. SCHMIDT K. SHI X., SONG Z., WEBBER C-.L., WEBER B., & SCHOLTEN T. (2017) - *Bryophyte-dominated biological soil crusts mitigate soil erosion in an early successional Chinese subtropical forest.* Biogeosciences, 14, 5775.

SEPEHR A., HASSANZADEH M. & RODRIGUEZ-CABALLERO E. (2018) - *The protective role of cyanobacteria on soil stability in two Aridisols in northeastern Iran.* Geoderma Regional, 16, e00201.

SKINNER S. & ENTWISLE T. (2004) - *Non-marine algae of Australia: 6. Cladophoraceae (Chlorophyta).* Telopea, 10, 731-748.

SMITH A.J E. (2004) - *The moss flora of Britain and Ireland.* Cambridge University Press.

STALEY D.M., WASKLEWICZ T.A. & BLASZCZYNSKI J.S. (2006) - *Surficial patterns of debris flow deposition on alluvial fans in Death Valley, CA using airborne laser swath mapping data.* Geomorphology, 74 (1), 152-163.

TEMINA M., KONDRATYUK S.Y., ZELENKO S.D., WASSER S.P. & NEVO E. (2005) - *Lichen-forming, lichenicolous and allied fungi of Israel.* Ruggell: A.R.A. Ganter Verlag K.-G. 384.

TUCKER B. & KURTZ L. (1961) - *Calcium and magnesium determinations by EDTA titrations.* Soil Science Society of America Journal, 25 (1), 27-29.

ULLMANN I. & BUDEL B. (2003) - *Ecological determinants of species composition of biological soil crusts on a landscape scale*. In: BELNAP J. & LANGE O. L. (Eds.), Biological Soil Crusts: Structure, Function and Management. Springer, Berlin, 203-213.

VALENTIN C. & CASENAVE A. (1992) - *Infiltration into sealed soils as influenced by gravel cover.* Soil Science Society of America Journal, 56 (6), 1667-1673.

VIJAYAN D & RAY JG. (2015) - *Ecology and diversity of Cyanobacteria in Kuttanadu paddy wetlands, Kerala, India.* American Journal of Plant Sciences, 6 (18), 2924.

WAINWRIGHT J. (2009) - *Desert ecogeomorphology.* In: PARSONS A.J. & ABRAHAMS A.D., (Eds.) Geomorphology of desert environments, 21-66, Springer, 674 pp.

WANG W.B., YANG C.Y., TANG D.S., LI D.H., LIU Y.D. & HU C.X. (2007) - *Effects of sand burial on biomass, chlorophyll fluorescence and extracellular polysaccharides of man-made cyanobacterial crusts under experimental conditions.* Science in China. Series C, Life Sciences 50, 530-534.

WEBB R.H. (2009) - *The Mojave Desert: ecosystem processes and sustainability.* University of Nevada Press, 481 pp.

WHITFORD W.G. (2002) - *Ecology of desert systems.* Academic Press, 343 pp.

WILLIAMS A.J., BUCK B.J. & BEYENE M.A. (2012) - *Biological soil crusts in the Mojave Desert USA: micromorphology and pedogenesis.* Soil Science Society of America Journal, 76, 1685-1695.

WILLIAMS A.J., BUCK B.J., SOUKUP D.A. & MERKLER D.J. (2013) - *Geomorphic controls on biological soil crust distribution: a conceptual model from the Mojave Desert (USA).* Geomorphology, 195, 99-109.

WILLIAMS J.D. (1994.) - *Microbiotic Crusts: A Review.* (Final Draft). U.S.D.A., Eastside Ecosystem Management Project Report. Unpublished data.

(Ms. received 2 August 2018; accepted 10 October 2019)

Edizioni ETS
Palazzo Roncioni - Lungarno Mediceo, 16, I-56127 Pisa
info@edizioniets.com - www.edizioniets.com
Finito di stampare nel mese di dicembre 2019