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Effect of biological soil crusts on soil chemical properties: a study from Tunisian arid ecosystem

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Abstract

Biological soil crusts (BSCs) composed of cyanobacteria, green algae, bryophytes, and lichens are a major biotic component of arid and semi-arid rangeland environments worldwide. They are recognized and studied in many parts of the world. However, they have been the subject of very few studies in Africa. The current study deals with the assessment of the influence of BSCs on soil chemistry in an arid ecosystem in Southern Tunisia. Our main objective is to test whether biological soil crusts are able to improve soil chemical properties. Our investigation showed that biological soils crusts had an expressive effect on soil chemistry. In fact, biologically crusted soils had higher levels of pH, electrical conductivity, organic matter, organic carbon, nitrogen, phosphorus, Ca, K, Na, Cl and lower C: N ratio compared to biologically un-crusted soils. The differences between crusted and un-crusted soils were statistically significant at 95% confidence. The PCA results demonstrate further that BSCs significantly enhance soil surface properties. These data support other studies revealing an improvement of the soil chemical properties by means of biological soil crusts.

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Introduction

In arid and semi-arid lands, which constitute 33-40% of earth's terrestrial surface (Kassas, 1995), the distribution of vegetation exhibits marked patchiness with discrete patches of vascular plants and open areas devoid of vascular vegetation (Valentin *et al.,* 1999). However, these seemingly open spaces between the higher plants are generally not bare of autotrophic life, but rather are covered by a community of highly specialized organisms (Belnap, 2001). These communities form a surface biological soil crusts (BSCs), or cryptogamic, cryptobiotic, microbiotic, or microphytic soil crusts (Harper and Marble, 1988) inhabit open spaces among vascular plants and beneath canopy spaces in arid and semi-arid grasslands, which are the potential natural ecosystem type on approximately 25% of the land surface of the earth (Shantz 1954), and shrubland ecosystems (Muscha and Hildm, 2006).

Biological soil crusts composed of bacteria, cyanobacteria, algae, mosses, liverworts, fungi and lichens, are a major biotic component of arid and semi-arid ecosystems worldwide (Eldridge and Greene, 1994). These organisms are recognized as indicators of landscape health (Eldridge and Rosentreter, 1998; Bowker *et al.,* 2008). In fact, they influence on critical ecosystem processes such as infiltration, carbon sequestration and nutrient cycling (Evans and Ehleringer 1993; Eldridge *et al.,* 2000). Indeed, they improve soil fertility in typically nutrient-poor systems (Belnap and Gardner, 1993; Evans and Ehleringer, 1993) and reduce erosion by binding soil particles (Eldridge, 1998). In addition, they reduce wind and water erosion, fix atmospheric nitrogen, and contribute to soil organic matter (Eldridge and Greene, 1994), seed ecology and seed banks (Belnap *et al.,* 2001; Eckert *et al.,* 1979) and vegetation diversity and density (Belnap *et al.*, 2001). Furthermore, in arid ecosystems, BSCs can enhance establishment of vascular plants by altering soil temperatures and improving soil water retention (De Falco *et al.,* 2001).

Biological soil crusts are recognized and studied in many parts of the world, including the United States, Australia, Spain, Israel and China. However the functional role of biological soil crusts communities has been the subject of very few studies in African rangelands. The aim of this paper was to examine the effect of these crusts on soil chemical properties. Investigations are based on the measurement of soil pH, electrical conductivity, organic carbon, organic matter, total nitrogen, available phosphorus, Ca, Na, K and Cl content in biologically un-crusted and crusted soils.

Materials and methods

Study site location and description

The investigation was conducted in El Gonna (34°42'34N, 10°31'54E), located at 20 km west of Sfax in Southern Tunisia. The climate type is Mediterranean lower arid with temperate winters (Emberger, 1955). The study site is characterized by a mean annual temperature of 18.3 °C and a mean annual precipitation of 191 mm. Soils are alkaline sandy loam, with friable caliches at 10-25 cm depth and gypsum outcrops (Jeddi and Chaieb, 2009). Perennial plant cover is below 40% and the landscape is dominated by *Stipa tenacissima* L.

Fig. 1. Biological soil crusts in the surveyed site.

The study site is characterized by the presence of biological soil crusts both in bare soil and under vascular plants (Figure 1).They are generally rugose during a wet season and smooth during a dry season. Biological soil crusts in this study area were heavily dominated by the cyanobacterium *Microcoleus vaginatus* and the lichen *Collema sp*.

Soil sampling

Soil sampling was conducted in March 2013 when the soil was dry, five randomly samples (depth: 1-3 cm) were collected in five replications from crusted and un-crusted microsites, oven dried at 105 °C for 24 h and sieved in a 2 mm sieve. These samples were collected far from plant patches to avoid their nutrients inputs. Subsamples of ~200 g were transported to the laboratory for analysis.

Soil chemical analysis

In fact that soil texture as abiotic factor is important factors that influence distribution of minerals, organic matter retention, microbial biomass and other soil properties (Scott and Robert, 2006), we measured silt and clay fractions for the un-crusted and crusted soils using the Jar test.

The following soil chemical properties were studied: pH, electrical conductivity (EC), organic carbon (C), organic matter (OM), total nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), sodium (Na) and chloride (Cl). Measurements of pH were determined by potentiometry in a 1:5 soil: water suspension using a portable pH meter. Electrical conductivity was measured by a conductivity meter. Soil organic carbon was determined by the Walkly black procedure (Nelson and Sommers, 1982). Phosphorus and total nitrogen content were measured by the Olsen's bicarbonate extraction (Olsen and Sommers, 1982) and Kjeldahl's method, respectively. Organic matter was estimated by multiplying the organic carbon obtained by 1.724~. K, Ca and Na content were determined using a Jenway PFP7 Flame Photometer. Cl content was measured using an ionometer.

Statistical analysis

To test the difference between the compared microsites in soil chemical properties evaluated and to assess the effect of biological soil crusts on modifying soil biochemistry and because the variables are non-normally distributed, we used the U-Mann-Whitney test. Values of probability lower than 0.05 were considered as statically significant.

We applied the principal component analysis (PCA) based on the correlation matrix between the components and soil chemical variables to explain most of the variance with the understudy variables. The elemental data suits obtained for the soil samples were subjected to cluster analysis treatment.

All analyses were performed using the statistical software package R.

Results

Effect of biological soil crusts on soil texture and chemistry

Biologically crusted soils have higher silt and clay percentages than biologically un-crusted soils. In fact, silt fractions were about 21%±5.11 and 32%±7.12 and clay fractions were about 11%±3.279 and18%±4.469 for the un-crusted and crusted soils, respectively.

Table 1. Results of the U-Mann Whitney test to evaluate differences in soil surface properties between microsites.

Soil chemical properties	Z	P value
pH	-2.611	<0.05
Electrolytic conductivity	-2.611	<0.01
Organic matter	-2.619	<0.01
Organic carbon	-2.627	<0.01
Total nitrogen	-2.619	<0.01
C : N ratio	-2.611	<0.01
Available phosphorus	-1.567	<0.05
Na	-2.619	<0.01
Ca	-2.627	<0.01
K	-2.619	<0.01
Cl	-2.611	<0.01

Mean values of soil chemical properties recorded in bare soil without and with biological soil crusts are presented in figure 2. Availability of organic matter, organic carbon and mineral nutrients in biologically crusted soils differed from that found in biologically un-crusted soils. In fact, they were all substantially higher in crusted microsite compared to un-crusted microsite. Indeed, microbiotic crusts increased soil pH from 6.96 to 7.58 and electrical conductivity from 1.39 ms/cm to 2.09 ms/cm.

Table 1 showed the result of Mann Whitney test of the understudy variables in crusted and un-crusted soils. The analysis of the data showed significant differences between the evaluated microsites in all soil surface properties measured. P value was <0.05 for pH and available phosphorus and <0.01 for the other variables.

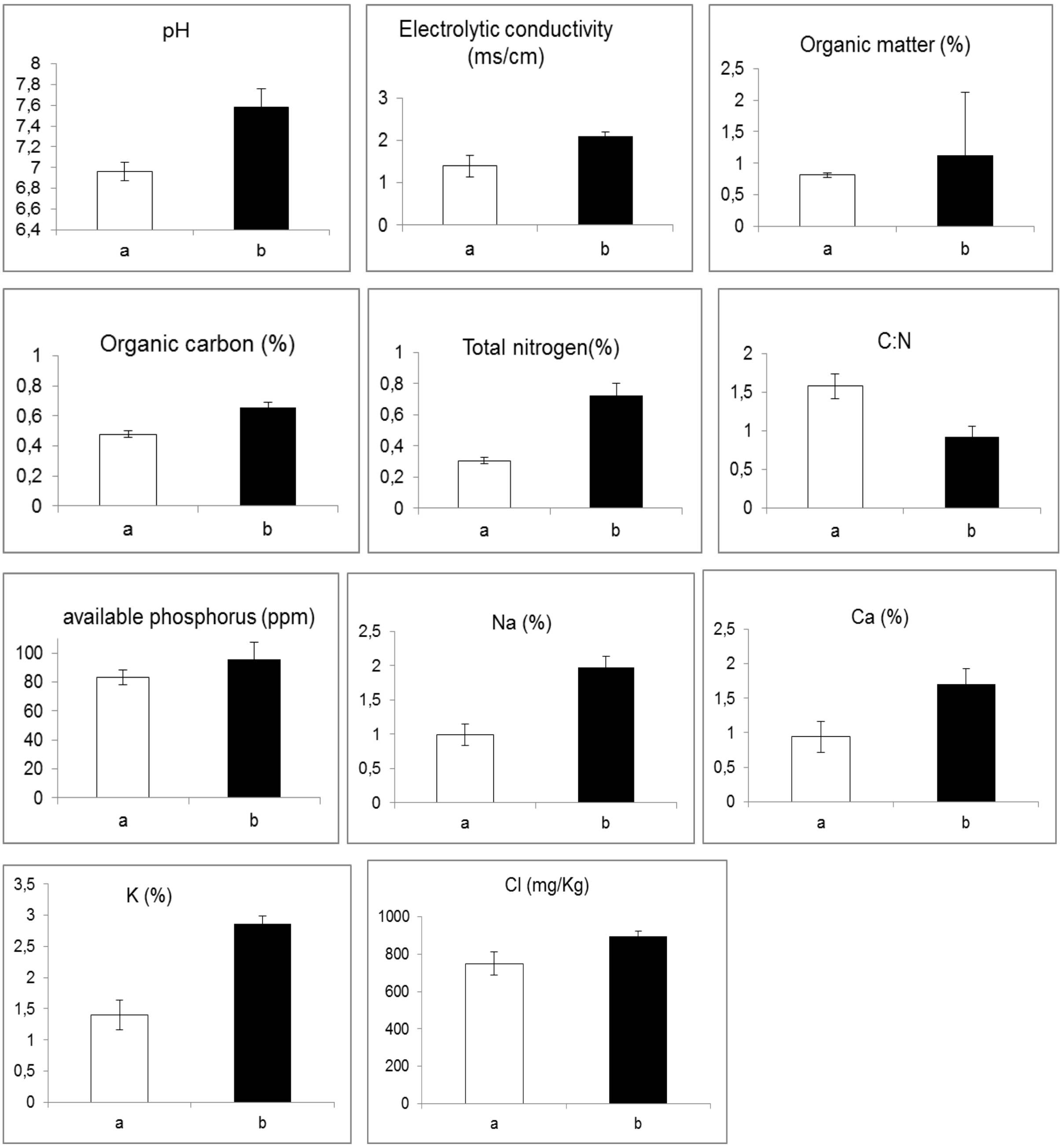

Fig. 2. Values of soil chemical properties measured under biologically un-crusted (a) and crusted (b) microsites.

The strong influence of biological soil crusts on soil chemical properties was also demonstrated using principal component analyses PCA (Figure 3). The first and second principal components are a result of the linear combination of the 10 sampling points (individuals factor map) and the 11 studied variables

(variables factor map) and both explained 80.72 % and 7.38 % of the variance, respectively. The first component was negatively correlated with the variable C: N and positively correlated with the other variables. Thus, the effect of the variation factor of the variable C: N led to a reduction of its values while the values of other variables increased. These variables correspond to the soil properties related to the presence of biological soil crusts.

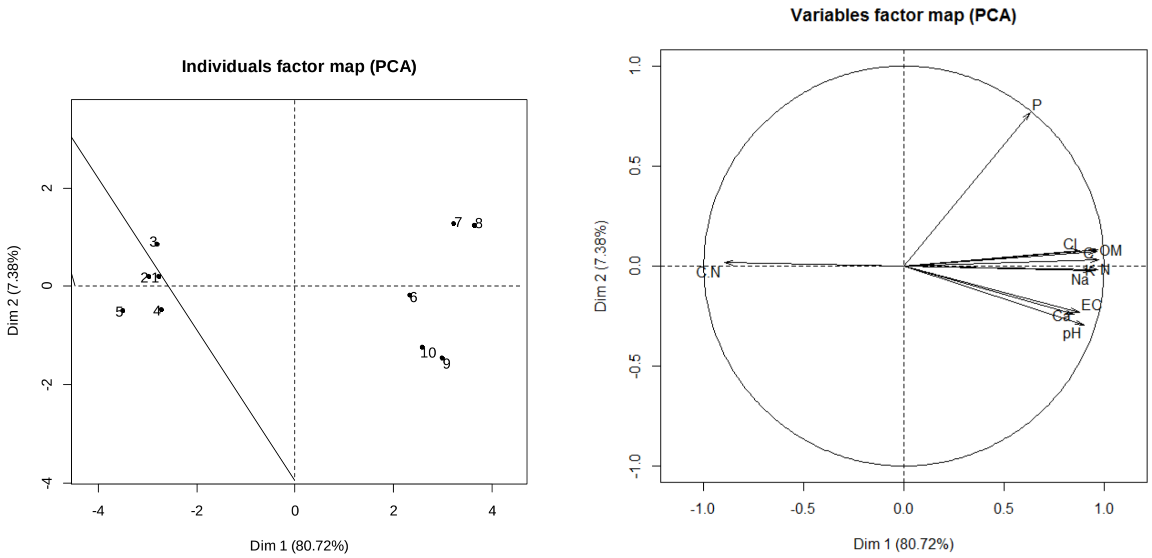

Fig 3. Principal component analysis of the influence of biological soil crusts on soil chemical properties: individuals factor map (1 to 5: samples without biological soil crust; 6 to 10: samples with biological soil crusts) and variables factor map.

Cluster analysis and samples grouping

Cluster analysis was applied to detect spatial similarity for grouping of the samples in relation to the measured soil chemical characteristics. The clustering procedure generated two groups of samples in a convincing way, indicating relatively high independency for each cluster (Figure 4). The cluster 1 includes soil samples without BSCs and the cluster 2 includes soil samples with BSCs. The results of cluster analysis consider the sampled microsites have different soil chemical characteristics.

Discussion and conclusion

Effect of biological soil crusts on soil functioning

Our results showed that BSCs significantly increase soil pH, this result corroborate with that of Garcia-Pichel and Belnap (1996). They increase also electrical conductivity; enhance organic and mineral nutrients levels and decrease C: N ratio. These results are in agreement with previous studies conducted in arid and semi-arid areas (Black, 1968; Harper and Pendleton, 1993; Belnap *et al.,* 2001; Harper and Belnap, 2001; Hawkes, 2003; Pendleton *et al.,* 2003). In fact, crusted soil surfaces often have a greater silt/clay fraction than underlying soils, or adjacent un-crusted soil surfaces (Belnap *et al.,* 2001); as our findings has shown. As a result, crusted soils have the greater total soil porosity which explains the higher soil electrical conductivity shown in the crusted microsites. Moreover, fine clay particles stick to the mucilaginous sheath material, notably when wet (Belnap and Gardner, 1993; Verrecchia *et al.,* 1995). The negatively charged clay particles bind positively charged plant macronutrients which increase soil fertility (Black, 1968). Belnap and Harper (1995) reported that the ability of the cyanobacterial sheaths to directly bind positively charged molecules might contribute to the increasing of nutrient availability.

While vascular plants provide organic matter to soils directly beneath them, large interspaces between plants which receive little plant material input presents high carbon contents due to the carbon contributed by biological soil crusts helping to keep plant interspaces fertile and providing energy sources for soil microbial populations (Belnap, 2001). The increases in soil organic matter contribute to reduce inorganic soil crusting and nutrient leaching losses, increase soil moisture retention and ameliorate compaction (Evans and Young, 1984; Tongway and Ludwig, 1990).

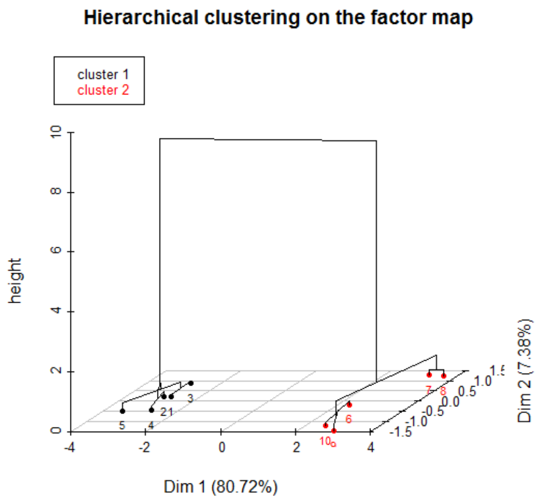

Fig. 4. Cluster analysis and samples grouping.

Anyway, all crust components secrete extra-cellular carbon within minutes to a few days of carbon acquisition (Belnap *et al.*, 2001). These secretions can represent up to 50% of the total fixed carbon in cyanobacteria (Lewin, 1956; Fogg, 1966). Thus, presence of BSCs increases soil polysaccharides and total carbon by up 300% (Rao and Burns, 1990; Rogers and Burns, 1994). The polysaccharide production is stimulated by Mg, K and Ca, which then results in greater binding of these nutrients (Belnap *et al.*, 2001). Besides, microbial polymers act as polyanions that prevents excess quantities of highly charged molecules such as heavy metals from approaching the cell surface, while concentrating growth-promoting nutrients present at low concentration in the surrounding environment (Lange, 1976; Geesey and Jang, 1990). This explains our findings reporting higher Ca, Na, K and Cl contents in crusted soils compared to un-crusted soils.

Nitrogen is thought to be a key element in determining community structure and succession (Tilman, 1986). Indeed, maintaining normal nitrogen cycles is critical to soil fertility and prevention of desertification (Dregne, 1983). The maximum input of nitrogen and other minerals occurs when the organisms are most active and this process is almost solely based on the cyanobacterial component of the crust, whether free-living or as part of lichens (Johnston, 2007). Nitrogen inputs from biological crusts have been estimated from 1 to 100 kg ha-1 annually (Harper and Marble, 1988) and are highly dependent on past and present water and light regimes, as well as species composition (Belnap, 1994). Nitrogen released from crustal organisms is readily taken up by surrounding vascular plants, fungi, and bacteria (Mayland and MacIntosh, 1966; Mayland *et al.,* 1966). Cyanobacteria and cyanobacterial-containing soil lichens can be an important source of both fixed nitrogen for plants and soils in desert ecosystems (Evans and Ehleringer, 1993; Belnap, 1995). In fact, up to 70% of the nitrogen fixed by cyanobacteria and cyanolichens is released immediately into the surrounding soil environment (Benlap *et al.*, 2001). Rogers and Burns (1994) and Harper and Belnap (2001) reported that the presence of BSCs increases surrounding soil N by up to 200%.

Crusts can be the dominant source of fixed N in semiarid ecosystems (Evans and Ehleringer, 1993), and this nitrogen appears to be available to higher plants (Mayland *et al.*, 1966). Indeed, stable isotopes show that soil crusts can be the dominant source of N for desert soils and plants (Evans and Ehleringer, 1993; Evans and Belnap, 1999).

Furthermore, the presence of crusts can lower soil C: N ratios which increase decomposition rates, making nutrients available faster to associated organisms (Kleimer and Harper, 1972).

Moreover, the phosphorus rates increase is accomplished by the binding of soil fines, which are relatively high in phosphorus content (Harper and Marble, 1988).

To put it in a nutshell, our findings demonstrated that biological soil crusts improved chemical soil properties and increased soil fertility in arid ecosystems. Thus, well-developed microbiotic crusts represent an indicators of better soil functioning.

Biological soil crusts: threat and need of restoration
Soil fertility losses is one of the most pressing problems involved in the degradation of ecosystem functioning and desertification in drylands (Bowker *et al.,* 2006). Our study and previous investigations revealed the key role of microbiotic crusts through the improvement of soil fertility. In fact, these organisms are considered essential components of healthy, functional ecosystems and both local and regional biodiversity (Eldridge, 2000). But, in spite of the fundamental roles they play in maintaining ecosystem structure and functioning, they are threatened by destruction which results in ecosystem disruption. Their loss is considered a major cause of land degradation (Belnap, 1995). Human impact is the number one cause of crust destruction (Belnap, 2003). Mechanical disturbances and trampling can cause compression of surface soils or overturn surface crust organisms, which bury potential surviving organisms or completely remove any material that may assist providing inoculants for natural recovery (Campbell, 1979; Johansen, 1993; Webb, 2002). Current evidence suggests that disturbance has profound effects on the BSC cover, species composition and the physiological functioning of soil crust organisms, and adversely affects the ecosystem processes which BSCs provide (Chiquoine, 2012). Some studies have suggested total BSC cover as an indicator of ecological health (Tongway and Hindley, 1995; Pellant *et al.,* 2000). With reduced BSC cover, erosion potential increases and can lead to decreased carbon inputs (Barger *et al.,* 2006) and nitrogen inputs (Barger *et al*., 2005; Barger *et al*., 2006; Evens and Belnap, 1999; Evens and Ehleringer, 1993). BSCs are quite susceptible to surface disturbance and may require decades for full recovery if unassisted (Bowker, 2007). Thus, restoration of BSCs should be undertaken when they can contribute toward reestablishment of a more highly functional ecosystem (Maestre *et al.,* 2011).

In conclusion, this investigation showed the influence of biological soil crusts on soil chemical properties and underlines the importance of these crusts as a soil improver and creators of resource islands in arid ecosystems by fixing carbon, nitrogen and other nutrients into the soil. In spite of their functional role, microbiotic crusts are often vulnerable to degradation (Belnap, 1995). The recovery of biological crusts may take decades, even hundreds of years; it depends on the ecosystem, BSCs community, and climate (Belnap and Eldridge, 2001). Protection of these crusts is important for ecosystem sustainability and maintaining the resilience of BSC communities to current and future climate changes (Chiquoine, 2012). Restoration ecologists should devote further attention to the degraded bio-crusts in accordance with the magnitude of this problem.

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