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Weathering of Carbonate Rocks by Biological Soil Crusts in Karst Areas

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ABSTRACT: The weathering of carbonate rocks by biological soil crusts (BSC) in karst areas is very common. It is helpful to understand the weathering mechanisms and processes for avoiding karst rock-desertification. The weathering of carbonate rocks by BSC in karst areas, namely the expansion, contraction and curl resulting from environmental wetting-drying cycles, was investigated and analyzed in this paper. The bulk density, area and thickness of BSC were determined and the weathering amount of limestone and dolomite per unit area of BSC was calculated as 3 700 and 3 400 $g \cdot m^{-2}$; the amount of biomass on the surface of limestone and dolomite was calculated as 1 146 and 1 301 $g \cdot m^{-2}$, respectively. Such an increased weathering amount was not only the result of chemical and physical weathering of BSC on carbonate rocks, but also the attachment and cementation of BSC to clay particles, dust-fall, sand particles, solid particles brought by strong air currents, wind and other factors in the surrounding environment, which may also be related to the special environment and the special time period. Based on the results obtained, a weathering mode of BSC is studied, and the mechanisms of weathering by BSC are discussed. In conclusion, we suggest that the mechanical force exerted by the expansion and constriction of gelatinous and mucilaginous substances through wetting and drying of BSC play a significant role in the physical weathering process of the carbonate substrates.
KEY WORDS: biological soil crust, dolomite, limestone, weathering amount, biomass.

0 INTRODUCTION

Biological soil crusts (BSC) are surface-bound assemblages of microorganisms that consolidate the soil into millimetre to centimetre thick crusts (Garcia-Pichel, 2002). BSC, dominated by lichens, mosses, cyanobacteria, and micro-fungi, grow and develop in a variety of environments including extremely cold, hot and arid lands wherever the lack of water restricts the settlement and development of higher plant cover (Belnap et al., 2012). The extent and degree of BSC development have an important influence on ecosystem structure and processes, including nutrient cycling, soil stability, biodiversity, erosion, and runoff (Belnap and Lange, 2003). The BSC influence on soil hydrology and erosion has been studied in dry lands across the globe, principally in North America, Israel, and Australia, which has consistently demonstrated that BSC reduce erosion and the disturbance of the crust surfaces can dramatically increase erosion rates (Barger et al., 2006; Eldridge, 1998; Eldridge and Kinnell, 1997). Despite their importance and the research work carried out in arid and semi-arid zones, we are still far from a general knowledge of the relationships between BSC, weathering processes and resulting landforms. The application of more specialized analytical techniques as well as the work of multidisciplinary scientific teams can help us to understand the effects of BSC on the rock weathering processes (Adamo and Violante, 2000). Many studies concerned with the long-term stability of architectural materials have contributed greatly to defining communities of organisms and the damage they cause to natural and synthetic materials (Souza-Egipsy et al., 2004; Sterflinger, 2000; Warsteid and Braams, 2000). However, the role of BSC in karst areas has seldom been attached any importance.

In order to further understand the mechanisms and processes of carbonate rock weathering by BSC in karst areas, the BSC on the surface of carbonate rocks in karst areas are investigated. The weathering amount and the biomass of BSC on carbonate rocks per unit area in a limited time are determined and a preliminary weathering mode of BSC is suggested.

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1 DESCRIPTION OF BIOLOGICAL SOIL CRUSTS

Through observations on the BSC and the surfaces where they grow, the main structure of BSC at sampling points can be

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described diagrammatically as in Fig. 1.

In this sketch, Level I is a bio-complex-layer, which is primarily made of microbiota (such as cyanobacteria, algae, lichen, moss and other microorganisms) and the complex formed by cementation of mycelium, rhizoid, secretion and solid particles on the rock surface; Level II (Level III) is tectorium, which is made of unconsolidated sediments and some microbes on the rock surface; below Level II is the bedrock, a carbonate rock.

Level I: BSC is an organic complex formed by the association of microorganisms, algae, lichen, bryophyte and soil particles, where organisms continuously attach and absorb dust-fall, sand particles, solid particles brought by strong air currents, wind and other factors in the surrounding environment and secrete organic matters to form an organic-mineral complexes. This level acts as an excellent absorbent and hygroscopic substance and therefore has good water holding capacity when enough moisture is available (Lian et al., 2010, 2008). When alternate wetting and drying is frequent, considerable physical weathering of the substrate rocks induced by Level I through Level II of BSC will occur rapidly.

Level II: a layer of tectorium, which includes some "drill" microbes, microbial secretion and incompletely weathered matters, etc.. This level has many undulating chippings or tunnels on the rock surface formed by physical, chemical and biological weathering. Organisms living in Level II can acquire the mineral nutrition from the bedrock and take the rock particles from weathering fragile surface because of wetting-drying cycle or other unclear reasons.

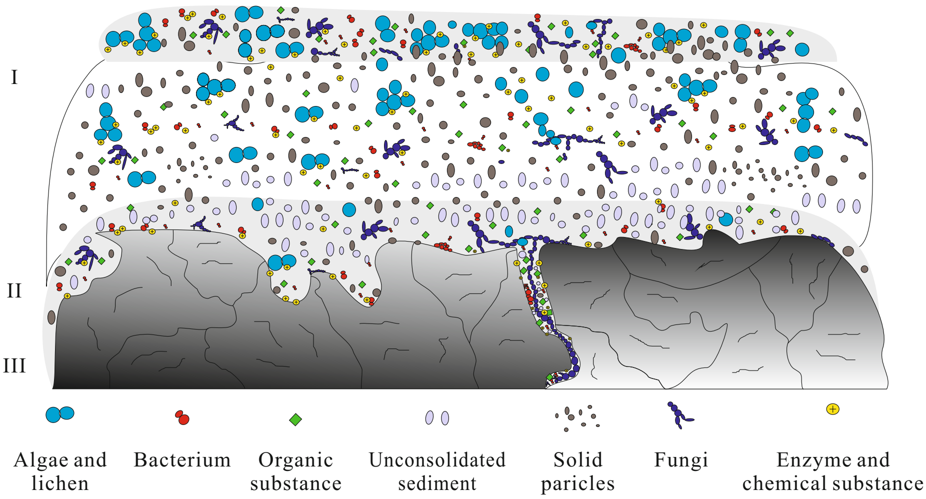

Figure 1. The main structure of biological soil crusts.

2 MATERIALS AND METHODS

2.1 Sampling Sites

The Aha Lake (26º33′4″N, 106º38′53″E) of Xiaohe Zone is situated in southeast of Guiyang, Guizhou Province, China. It has a subtropical humid climate, accompanied by plateau and monsoon climates. The annual average air temperature is 15.3 °C with a maximum temperature of 35.1 °C and a minimum temperature of -7.3 °C. The average annual precipitation is 1 129.5 mm, the spatial and temporal distribution of precipitation is uneven, mostly concentrated during April to October, which accounts for 85% of the annual precipitation. The area is dominated geologically by dolomite and limestone. Topographically, it forms a steep slope stretching along the Aha Lake. There are some rivulets along the slope. The surface alternates between bare rocks and rocks covered with BSC, shrubberies or deciduous trees, and weathered rock. The amount of rainfall has a major influence on the environment of the Aha Lake area.

2.2 Sample Collection

BSC were collected during late summer in 2008 from 30 sites within the lower basin of the Aha Lake. The samples on limestone surfaces were collected from the top of the Aha Hill along a 3 km transect and the vegetation along the transect contained deciduous shrub, while the samples on dolomite surfaces were collected from the top of the Xiaochehe Hill along a 5 km transect and the vegetation along the transect also contained deciduous shrub. At each site, a spatula was used to sample a 10×10 cm area of BSC from the central part of the area occupied by the crust. Samples (1st and 2nd layer, the BSC samples were estimated to grow for 10–20 a) were placed in Petri dishes for transportation to the laboratory, taking care to preserve the integrity of the crust. All substances on rock surfaces, in each 10×10 cm area, were swept into clean plastic bags with a fur brush. Then, the rock from the two sections were sampled and the mineral compositions of rock samples were analyzed by XRF (X ray fluorescence) (PW4400, Axios) and XRD (X ray diffraction) (D/Max-2200, Rigaku).

2.3 Taxonomic Determination

Initial identification was carried out for all the BSC samples. Identification of cyanobacteria was carried out by placing the upper portions of the soil crusts in glycerin-gelatin for microscopic examination (Egan, 1972). Mosses and lichens were identified by microscopic observation (Nash III and Johnson, 1975; Shushan and Anderson, 1969).

2.4 Bulk Density (ρ_a) Determination

The bulk density (ρ_a) of BSC was determined by a coating process (Blake and Hartge, 1965) using the following protocol. Three samples of BSC were taken from each Petri dish. The volume of each sample was ~3–5 cm^3. Then a string was tied around each sample with thread so that it can hang freely from a 2" length of thread with a loop on the end. Each BSC sample was placed in a numbered and pre-weighed beaker. The beakers containing the BSC were dried in the oven (≤70 °C) over night and then cooled using a desiccator. The beakers containing the BSC were weighed and the data were recorded (subtracting the weight of the beaker from the combined weight of the BSC and beaker). A cup of paraffin wax was melted and stabilized between 55 and 60 °C. Each BSC sample was dipped in the paraffin and was dried, making sure that the sample was entirely sealed. The coated BSC sample without the beaker was weighed and its weight was recorded. The BSC samples were immersed in water and the beaker was weighed on a triple beam balance using a ring stand to hold the beaker of water positioned just above the balance pan (note: if bubbles appear on the surface of the coated BSC, they break free and rise to the surface, this observation was recorded as "BBL". If the BSC floats, the observation was recorded as "Floater"). The BSC coating was peeled off and returned to its beaker. Each beaker was filled with water making the BSC soggy, which makes the crusts fall apart. The contents of each beaker were wet sieved through a 2 mm sieve. All but the <2 mm fraction was removed and placed in the oven to dry. The >2 mm contents of each beaker were weighed and the weights were recorded.

2.5 Superficial Area (*S*) Calculation

The shape of BSC on the surface of carbonate rock is significantly influenced by its habitat, such as temperature, humidity, light irradiation and rainfall. The moisture in BSC is susceptible to vaporization causing the BSC to curl and twist, which will make it difficult to determine the superficial area of BSC. After being sprayed with enough water, the curling crust sample could absorb moisture and lie flat on the Petri dish. Then, the exterior contour of the tile crusts was scanned and plotted. The scanned images were then imported to AUTOCAD software. The superficial area of the crust was calculated using the "region" command and "inquiring out area" command in AUTOCAD.

2.6 Biomass and Weathering Amount on Carbonate Rock of BSC per Unit Area

Because the constituent parts of the crust splice tightly to each other, it is difficult to separate and treat them with current methods. In order to estimate the total weight of BSC and the first layer weight of BSC, Biostrome (I) was roughly calculated as the biomass of BSC, which was calculated by its thickness, area, and bulk density. The total biostrome weight of BSC (W_1, g) was obtained using the following formula

$$W_1 = \sum_{i=1}^{15}(S_i \times h_i \times \rho_{ai})$$

where, W_1 is the calculated gross weight of BSC (g), S_i is the superficial area of the *i*th BSC (cm^2), h_i is the average thickness of the *i*th BSC (cm), and ρ_{ai} is the bulk density of the *i*th BSC ($g \cdot cm^{-3}$).

The weathered amount of carbonate rock per unit area of BSC (ξ, $g \cdot cm^{-2}$) can be calculated using

$$\xi = \frac{W_0 - W_1 + W_s}{\sum_{i=1}^{15} S_i}$$

where, W_0 is the gross weight of total BSC on different type rock surfaces (g), W_1 is the gross weight of biostrome of BSC (g), W_s is the gross weight of unconsolidated sediment in tectorium (g), S_i is the superficial area of the *i*th BSC (cm^2).

The biomass of BSC per unit area (φ, $g \cdot m^{-2}$) can be obtained by

$$\varphi = \frac{W_1}{\sum_{i=1}^{15} S_i}$$

where, W_1 is the gross weight of biostrome of BSC (g), S_i is the superficial area of the *i*th BSC (cm^2), φ can be used to evaluate roughly the weathering state of the carbonate rock by BSC.

3 RESULTS AND ANALYSIS

Based on our investigation, the BSC were characterized based on texture and the dominant organism, and most of them are dark brown in crusts with a flater surface containing predominantly cyanobacteria and algae.

The selected sampling sites were deprived of vegetation, where crusts were spread on the rock surface (Fig. 2). This type of crust occupies up to 60% of the rock surface in this area.

The results of the complete rock analysis and mineral composition analysis of rock samples are provided in Tables 1 and 2. The bulk densities, areas, biostrome thicknesses and the weight of biostrome of 30 samples are given in Table 3.

Based on the measurement of 30 samples, the biostrome thickness of each BSC varied, generally ranging from 0.5 to 2.0 mm. After measuring different positions of each crust, most

Figure 2. Biological soil crusts samples on limestone surface.

Table 1 The XRF analysis result (wt.%)

Sample	MgO	CaO	P_2O_5	LOI
Limestone	1.13	57.80	0.01	42.81
Dolomite	20.87	35.81	0.04	45.03

positions had a thickness of 1.5 mm.

From the above tables, the total weight of the 15 BSC on limestone is 437.81 g; the gross weight of unconsolidated sediment in the tectorium is 82.48 g; the gross weight of biostrome (I) is 122.68 g; the total area is 1 070.58 cm^2; the weathering amount per unit area of BSC to limestone was calculated as ξ=0.37 $g\cdot cm^{-2}$, which was regarded as the weathering amounts of the limestone by BSC.

The biomass per unit area was calculated as φ=1 146 $g\cdot m^{-2}$.

The weight of 15 BSC on dolomite is 402.44 g; the gross weight of unconsolidated sediment in tectorium is 68.93 g; the gross weight of biostrome is 129.42 g; the total area is 994.44 cm^2; the weathering amount per unit area of BSC to dolomite was calculated as ξ=0.34 $g\cdot cm^{-2}$.

The biomass per unit area was calculated as φ=1 301 $g\cdot m^{-2}$.

The biomass per unit area on limestone and dolomite is 1 146 and 1 301 $g\cdot m^{-2}$, respectively. The biomass of BSC on carbonate rock is quite large, which demonstrates that the interaction between BSC and rock is active and the related elemental bio-geochemical processes are strong. As a result, the chemical weathering should be stronger. The XRF analysis result (Table 1) indicates that the content of MgO and P_2O_5 in dolomite is greater than that observed in the limestone. Since nutritive materials and essential mineral elements are required, the mineral content in dolomite is greater than that in limestone. Therefore, the biomass per unit area in dolomite is greater than that in limestone.

The weathering amount per unit area of BSC to limestone and dolomite is 3 700 and 3 400 $g\cdot m^{-2}$, respectively. In addition, the weathering amount of limestone is higher than that of dolomite. From the XRD analysis result (Table 2), the content of calcite in limestone is 99.32%, which is much greater than that in dolomite (14%). Ascaso et al. (1982) studied weathering of limestone and dolomite by four different kinds of lichen and they found that oxalic acid secreted by lichens effectively had dissolved calcite in the above rocks, which resulted in a great reduction of the main mineral content. Acidic metabolites penetrated along the native limestone joints or cracks, which brought on the weathering of the limestone surface. Compared to other rock types, limestone is most vulnerable to biological

Table 2 The XRD analysis result (wt.%)

Sample	Calcite	Dolomite	Quartz	Montmorillonite
Limestone	99.32	0.51	0.17	-
Dolomite	14.00	85.20	-	0.79

Table 3 Bulk densities, Superficial areas, biotrome thicknesses, and the weight of biostrome

Rock type	No.	Sample No.	Bulk density ($g\cdot cm^{-3}$)	Superficial area (cm^{-2})	Biostrome thickness (cm)	Calculated weight (g)
Limestone	L	L1-1	0.59	31.59	0.15	2.80
		L1-2	0.49	42.02		3.09
		L1-3	0.68	28.89		2.95
		L1-4	0.81	51.85		6.30
		L1-5	0.54	62.47		5.06
		L2-1	0.89	98.53		13.15
		L2-2	0.82	77.65		9.55
		L2-3	0.62	82.07		7.63
		L2-4	0.79	93.17		11.04
		L2-5	0.50	103.25		7.74
		L3-1	1.19	83.81		14.96
		L3-2	0.91	67.02		9.15
		L3-3	0.84	74.87		9.43
		L3-4	0.91	71.22		9.72
		L3-5	0.66	102.17		10.11
Dolomite	D	D1-1	0.82	28.65	0.15	3.52
		D1-2	0.82	29.17		3.59
		D1-3	0.93	42.59		5.94
		D1-4	0.79	58.12		6.89
		D1-5	0.78	63.87		7.47
		D2-1	0.99	87.59		13.01
		D2-2	1.01	98.64		14.94
		D2-3	0.89	92.16		12.30
		D2-4	0.74	101.35		11.25
		D2-5	0.69	93.87		9.72
		D3-1	1.12	73.62		12.37
		D3-2	0.94	50.27		7.09
		D3-3	0.75	48.63		5.47
		D3-4	0.83	63.32		7.88
		D3-5	0.85	62.59		7.98

weathering, as dissolution of oxalic acid and other simple organic acids on limestone minerals are far stronger than that of other minerals (Syers and Iskandar, 1973). Such an increased weathering amount was not only the result of chemical weathering of BSC on carbonate rocks, but also the attachment and cementation of BSC to clay, dust-fall, soil particles, sand particles, solid particles brought by strong air currents, wind and other factors in the surrounding environment. Formation of BSC on carbonate rock surfaces strengthens the ability of holding up solid particles and accumulation of rock water. With the growing of BSC, a continuous weathering process occurs on the surface of carbonate rocks. The BSC capture the particles which are formed by the weathering process and some attach to the BSC. However, the detailed amount of captured substances and fixed exotic matters by BSC will still need further study. The experimental data may not be powerful to declare the weathering amount per unit area of BSC to limestone and dolomite in a short period of time, and it is not sure whether the rock surface can be weathered by BSC persistently, and whether the lower bedrock can be protected from the chemical and physical weathering, or which is dominant one. In fact, the data here is lager than that in the available reports on the weathering amount in karst area by using different methods (Feng et al., 2013).

The BSC on the surface of carbonate rocks are prone to dehydration and the crust will stiffen and curl due to evaporation. During the curling process, some solid particles will be taken up because of cementation to the BSC. At the same time, the mycelium inside the inner carbonate rock loosens up some mineral particles, which will make the surface of the rock loose. Whilst a large number of uncemented soil, mineral particles and sand are exposed on the rock surface, the captured substance and weathering product will be easily lost under the influence of physical factors such as wind and rain. Absorbing adequate moisture from humid air, BSC re-adhere to the surface of carbonate rocks. Hyphae and rhizoid of fungi, lichen, algae in the biostrome of BSC are inserted into the rock interior through various voids or micro-fractures in the rock, which will go on weathering at the rock surface, as shown in Fig. 3.

In karst areas, the expansion, contraction and curling of BSC resulting from environmental wetting-drying cycles accelerated the weathering process of rock and produced numerous rock fragments. These fragments, ranged from 1 to 50 mm in size along their longest axis, typically adhered to, or were embedded within the fungal hyphae (Viles, 2005). These particles of rock are likely plucked, probably from the rock surface, on contraction of the thalli of the BSC during the drying phase. It is therefore concluded that, in conjunction with chemicals excreted by the BSC, this process could play a significant role in the karstic pedogenesis.

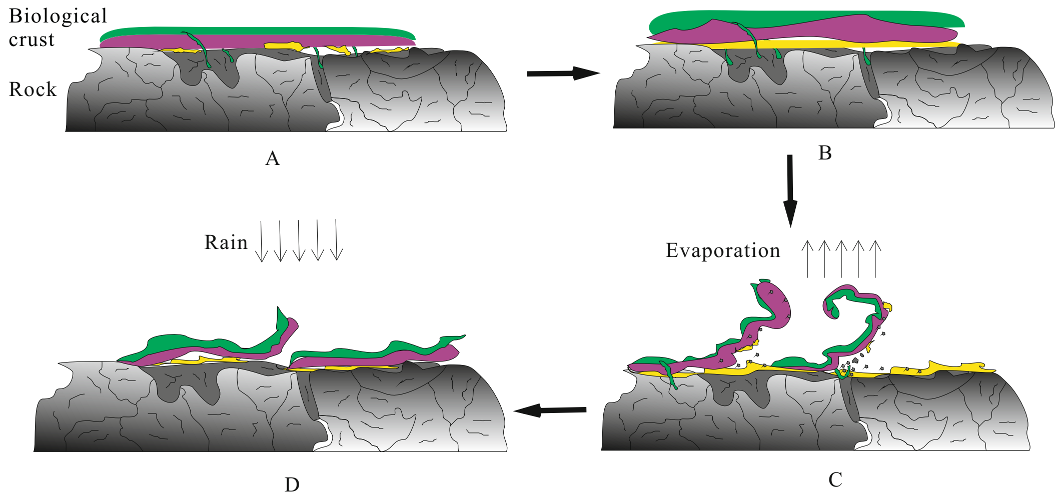

Figure 3. The weathering mode of biological soil crusts. A. BSC on rock surface; B. growing BSC; C. curing BSC due to evaporation; D. BSC of absorbing moisture.

4 CONCLUSIONS

The evidence presented by numerous investigations of the interface between BSC and their carbonate rock substrates strongly suggests that the weathering of rocks can be accelerated by the growth of BSC. The effects of BSC on the rock substrates can be attributed to both physical and chemical processes. The physical effects are reflected by the mechanical disruption of rocks caused by hyphal penetration, expansion and contraction of the BSC thallus. Moreover, the weathering process of rock is accelerated by the wetting-drying cycles of the BSC. BSC also have a significant impact on the chemical weathering of carbonate rocks due to the excretion of various organic acids, particularly oxalic acid, which can effectively dissolve rocks and chelate metallic cations. As the result of the weathering induced by BSC, many rocks exhibit extensive surface corrosion. At last, the attachment and cementation of BSC to the exotic dust-fall, sand particles, and organic matters brought by wind and other environmental factors undoubtedly increase in largely the weathering amount of BSC to limestone and dolomite.

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