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Soil Air Water

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Review

The Study of Biological Soil Crusts: Hotspots and Prospects

Biological soil crusts (BSCs), which cover 35% of the continents and exceed 70% of the living cover in parts of region, play important ecological roles in the evolution of soil–water–plant systems in arid and semiarid areas. Since the 1980s, studies of BSCs have become hot topics in physical geography. By reviewing the last 30 years of study reports, the present paper proposes the following future research focus: (1) Understanding the function of BSCs in carbon and nitrogen fixation in the micro-scale (block), monitoring its distribution patterns in the macro-scale (region) by remote sensing technology and geographic information systems, and evaluate the role of carbon and nitrogen fixation in the whole ecological system. The response of BSCs to global climate change should also be evaluated. (2) Studying techniques for the artificial fast cultivation or restoration of BSCs, and implementing engineering propagation and application of artificial BSCs, and determining the appropriate parameters for environmental criteria, including light, temperature, soil water moisture, and fertilizer, among others. Artificial cultivation and rapid propagation techniques could present significant perspectives for engineering applications.

Keywords: Carbon/nitrogen fixation; Ecological function; Fast cultivation; Micro-/macro-scale

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1 Introduction

Biological soil crusts (BSCs) are a highly complex community of mosses, cyanobacteria, lichens, bacteria, or fungi, etc., their main biological organism composition and primary forming mechanisms can be seen in Fig. 1. The coverage area of global BSCs is > 35% of the continents, and, in some parts of the world, could be > 70% of the living cover [1]. BSCs significantly affect various ecological processes, such as rainfall infiltration, soil erosion, seed germination [2–4], and so on, play the role of main primary producer, and indicate the cycle of carbon, nitrogen, and other main elements [5], their specific biological functions were summarized and listed in Tab. 1. BSCs researches has been performed in a wide variety of environments, from cold-region deserts, subalpine and alpine belts, and snowy areas to the hot deserts in North America, Asia, Africa, and Australia, and dry and hot steppes in east of the Mediterranean and central Europe, among others (Tab. 2).

Research reports from central Asia and China were relatively few in number before the 21st century. However, recent studies by Chinese scholars have produced significant results, many of which have been cited and acknowledged by foreign researchers [6]. Studies on the development mechanisms and ecological functions of BSCs have become the hot spot of physical geography in China [7–9]. Based on a review of recent advances in BSCs research, the present paper identifies the current hotspots in BSCs studies and proposes several prospects in future research.

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2 Current hotspots of BSCs studies

2.1 Remote sensing monitoring

Due to their ecological importance and vulnerability to disturbances, the presence, disappearance, and distribution of BSCs supply valuable indications on the desertification and climate change and so benefit to scientifically manage the ecosystem of desert regions [10]. Mapping the distribution of BSCs has become an increasingly in-demand task as it supports the protection of desert regions. Other works in this field mainly focus on the use of remote sensing data to classify or map BSCs over the past two decades [11–14]. As the first research group, Graetz and Gentle [15], measured the reflectance values of lichen crust although they did not perform further analysis of the data. The spectral characteristics of BSCs or their species components were investigated by a certain research studies [12, 16–20]. Wessels and van Vuuren [14] recognized that mapping BSCs relying on remote sensing images was feasible, and they effectively identified lichen crust in the Namibia desert, through false color composites of Landsat Thematic Mapper 3 data (TM bands 4, 5, and 7). In Nizzana, Hill et al. [21] compared both true color air-photos and hyperspectral imagery at around 10 m spatial resolution to identify BSCs, and successfully acquired BSCs patterns. However, BSCs while presenting with plants together, can't be differentiated from in the same pixel.

To detect cyano BSCs, The crust index (CI) was established by Karnieli [12] using aerial photograph and Landsat TM data. Using

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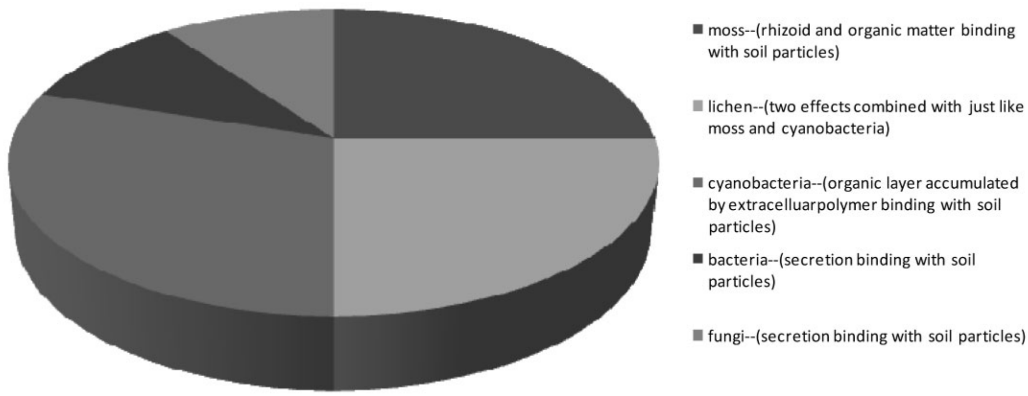

Figure 1. The sketch map of main biological organism of BSCs and its forming mechanisms.

Landsat ETM+ images, the by Chen et al. [22] proposed biological soil crust index (BSCI) could be used for identifying lichen-dominated BSCs in the case study in the Gurbantonggut Desert, Xinjiang, China. However, they found that lichen-dominated BSCs cannot be distinguished using this approach although a Kappa coefficient of 0.82 and an overall accuracy of 94.7% for crusted/uncrusted detection were achieved. They proposed that vast measurement and comparison of lichen-dominated BSCs from various study land using the new index were only way to enable more accurate separation of such BSCs from the background. Zhang et al. [23] found that, spatially, lichen and moss crusts mainly distribute in the south of the Gurbantunggut Desert. The crust cover becomes sparse in the central and northern parts of the desert, and is absent in the western and eastern parts of the desert. Unlike the deserts in the United States or Australia, however, liverworts are quite uncommon even under the canopies of vascular plants, such as *Haloxylon persicum* and *Ephedra distachya*, in the Gurbantunggut Desert in China.

Weber et al. [24] found that not only CI (cyanobacteria-dominated BSCs) but BSCI (lichen-dominated BSCs) produced widely overlapping results for distinguishing BSCs from bare soil. CI method only classified 17.8% of the study area as BSCs, the ground without crusts were incorrectly classified as BSCs. The classification BSCI was 20.9%. To get a higher classification, they put forward continuum removal crust identification algorithm (CRCIA), the application conducted in the Northern Cape Province, South Africa revealed good classification results that 45 of the 49 BSCs validation points were correctly classified as BSCs, and that 42 of the 46 non-BSC validation points were in fact not classified as BSCs with a Kappa index of 0.831 [24]. They also pointed out a few potential distractions such as climatic parameters (especially precipitation), lower crust coverage (5–10%), and combinations between crusts and canopy, the best classification could be realized while land was covered only by crust and entirely void of vegetation [24].

Besides the discussion above regarding the distribution of BSCs based on remote sensing, other researchers have studied the factors that affect the spectral characteristics of crust. Ustin et al. [25] evaluated the effects of soil disturbance, increased summer rainfall, and dry nitrogen deposition on spectral detection in southwestern Nevada, USA. The results showed that disturbance treatments are easily to be identified in color-IR imagery, disturbed and irrigation treatments and combinations of these with nitrogen treatments also could be observed. Nitrogen treatments did not show significant difference from controls unless combined with irrigation or disturbance treatments. Karnieli et al [26] found significant differences between the spectra of dry and wet crusts, therefore, interpretation mistakes may occur more easily when the interpretation method is established through the difference between BSCs and other objects under only one water content. Chen et al. [22] found that BSCs with hydration present more obvious spectral absorption, thus, remote sensing may be better performed under dry conditions. Fang et al. [27] found that the spectrum characteristics of wet moss crust was similar to *Artemisia ordosica* Krasch., and the spectrum of dry moss crust was similar to that of soil, resulting in a 0.35 difference in normalized difference vegetation index (NDVI) between dry and wet moss crusts with 100% coverage. Furthermore, the composition and stage of BSC significantly affects its spectrum; e.g., large differences

Table 1. The main biological effects of BSCs on soil, hydrology, and vegetation

Soil		Hydrology		Vegetation	
C, N, SOM	Accumulated	Infiltration/runoff	Both increase and decrease reported, runoff is opposite to infiltration	Deep rooting plant	Negative impact
Stability	Increased	Evaporation	Depending on stage of evaporation	Shallow rooting plant	Positive impact
Erosion	Decreased	Soil moisture	Determined by balance between infiltration and evaporation		
Always positive influence		Affected by soil texture, BSCs types, and climate condition etc.		Generally, soil moisture shallow due to BSCs' water holding and infiltration reducing	

Table 2. Major BSCs study areas in different countries around the world from 1991 to 2010

Continent	Country	Study area
Asia	China	Loess plateau Gurbantungggut Desert Tengger Desert Horqin Desert Inner Mongolian steppe Mu Us Desert
North America	USA	Colorado Plateau Sonoran Desert Mojave Desert Chihuahuan Desert Great Basin Desert Florida shrubland, Massachusetts seashore, Oregon prairies, Wyoming steppe, Ohio, Michigan sand, New Mexico
Europe	Israel	Negev desert
	Spain	Southeast Spain
Oceania	Australia	West desert
Africa	Namibia	Namib desert
	Botswana	Kalahari desert
Antarctica		Glacier foreland

were observed in moss crust between May and October. Zaady et al. [28] found that the BI (BSC index) can serve as a good indicator during the early years after a disturbance, when relatively few microphytes are established in the soil surface. Later, when the BSCs become thicker and contain more biomass, the NDVI is a better indicator. The NDVI was found to be a better indicator for the succession dynamics of the soil surface because it shows relatively higher correlation values during the dry season. Karnieli [12] found that BSCs dominated by cyanobacteria containing phycobilin pigments have a higher reflectance at blue wavelengths, which was not observed in the crusts dominated by lichen. A portable spectrometer was an efficient tool for rapidly measuring the temporal and spatial dynamics of BSCs without disturbing the surface. So far, universal methodology to map BSCs has still not been achieved by many attempts [29], although crust samples characterize obvious absorption feature at approximately 680 nm. Only if the seasonal difference and its relationship with the environmental factors (water content) of the BSC spectrum are understood, can the real distribution of crusts in a certain region be obtained by remote sensing means.

2.2 Artificial cultivation attempts

Because BSCs have a large number of positive ecological effects, researchers have attempted to artificially establish them using single or multiple species of BSCs, just like vascular plants construction, to improve ecology. In 2001, Wei, a Chinese academician of CAS, put forward the concept of ''BSC carpet engineering to control deserts''; his main idea was to create artificial BSCs through modern biological technology and spread them on shifts and to realize control of the sand. In 2002, his research group explored the specific carpet engineering technique, and separated, cultured, and stored many types of epiphytes and lichen bacteria, providing a large corpus of microorganisms for the inoculation and development of BSCs. In 2005, several institutes including Institute of Microbiology, Chinese Academy of Sciences (CAS), Cold and Arid Regions Environmental and Engineering Research Institute of CAS, Wuhan Institute of Hydrobiology of CAS, Xinjiang Institute of Ecology and Geography of CAS, and Institute of Soil and Water Conservation of CAS & Ministry of Water Resources, were combined together, ''biological soil crusts carpet engineering'' started normally [30].

At present, there are two approaches used to build up cyano-dominated BSCs: the inoculation method and the ''mosaic'' method [31]. Inoculated artificial BSCs are more applicable in real field conditions through adding monospecific cultures of BSCs organisms to a sterilized soil substrate and allowing establish BSCs, difficult manipulation of evenness is disadvantage of this approach. Mosaics, field-collecting small pieces of BSCs and reassembling them on uncrusted soil, can avoid the organisms of BSCs to be damaged [31, 32], and the spatial arrangement of evenness and abundances of BSCs organisms were easily manipulated [33]. Obviously, mosaics have a limitation: although experiment controls are easy to produce, that a certain area of crust was inoculated means that an equal area of crust was destroyed at the same time. Therefore, inoculation is more effective method of building up BSCs within a short period of time by lab cultivation. Creation of the appropriate conditions for cultivation must first be performed before promotion of BSC build-up.

Compared with other microbes, BSC cyanobacteria are easier to culture. Hu et al. [34] thus proposed that incorporates of cyanobacteria is perhaps the best way to create cyanobacterial or eukaryotic algal crusts. In recent years, many researchers have worked on such practices. Since 2000, the Institute of Hydrobiology of CAS, with the Institute of Forest Science in Mongolia, established a 200 ha demonstration region using artificial cyanobacteria soil crust in the Hobq desert; the method employed was found to be a feasible and effective method of controlling sand [35]. Tang et al. [36] reported similar research conclusions, finding that artificial cyanobacteria soil crusts can enhance soil enzyme vigor and accelerate soil development. Wang et al. [37] tested the feasibility of cyanobacterial inoculation for biological crust formation in desert areas of Inner Mongolia in China. Their results showed that cyanobacterial and algal cover increased up to 48.5% and a total of 14 cyanobacterial and algal species were identified. BSCs thickness, compression, and chlorophyll a content increased, moss species even appeared in the second year. Diverse vascular plant communities composed of 10 and 9 species were established by cyanobacterial inoculation on the windward and leeward surfaces of dunes after 3 years. The inoculation experiment in the Hobq desert showed that the average depth of artificial BSCs reaches 2.23–5.36 mm, their coverage is 70%. The compressive strength of algal crusts was enhanced by increases in algal biomass from an undetectable level to a value as high as $9.6\ \mathrm{mg\,g^{-1}}$ dry soil. The higher the algal biomass became, the thicker were the algal crusts formed. However, the compressive strength did not immediately decrease but remained relatively steady while the algal biomass decreased [38]. The biomass and exopolysaccharide production by *Microcoleus vaginatus* Gom. were not linearly related to temperature, light, and renewal rate; when the temperature was $30 \pm 2°C$, light was $600–700\ \mu E\,m^{-2}\,s^{-1}$, and then renewal rate was 35%, reasonable biomass and amylase can be realized [39]. Our results indicated that the moss-dominated crust grows best in the condition of 15°C, low Knop as the culture medium, compared to other treatments [40].

McKenna Neuman et al. [41–43] improved the approach to cultivate moss protonemata, while Backor and Fahselt [44] extended the approach to lichen mycobionts and synthetic lichens, although with great difficulty. The leaf axil cells and the leaf base cells could divide and form new plants through the process as follows: leaf axil cells and leaf base cells → primordium → protonema → gametophores → new plants [45]. Xu et al. [46] discussed the use of *Tortula desertorum* to establish moss-dominated crust. They found that in situ soil is the best cultivation media because the corresponding more protonema and shoots with explants. Detached green leaves as explants were induced abundant protonema in agar-solid Knop medium after 1 month as day/night temperature and humidity were set at 20/10°C and 60–85%. After 2 month, protonema transplanted into sand with liquid Knop medium under 25/15°C (day/night), moss-dominated crusts formed. Although some discussions were reported by the laboratory under artificial conditions, the results were very different from those in natural conditions. Tian et al. [45] found that the plants in the field were shorter and stronger than the ones indoors, their internodal distances were shorter, their leaf cells shorter and wider, and their leaf acumen was longer, although their reproductive characteristics were similar. A study of the effects of physiological stress due to partial hydration/rapid dehydration cycling on moss crust showed that chlorotic shoots, compared with green shoots, exhibited significantly reduced photochemical potential, sex expression, and lower rates of growth and productivity; however, older leaves from chlorotic shoots did not show the typical decline in vigor, suggesting that stress primarily affects younger tissues [47]. Under the natural condition, *Bryum argenteum* moss quadrates with removed crusts reached the previous coverage 70% within (3–4) years. Utilizing the powerful reproductive ability of fragments of stems and leaves, moss crust was artificially cultured by broadcasting plants and offshoots; developed *B. argenteum* species survived after 7 days, and the new plants occupied the uncovered space of the quadrates within the first month. However, more treatments should be adopted to extend moss growth because the plants began to wilt 3 months later and all the plants died after 2 years [45].

Maestre et al. [48] evaluated the influences of inoculation type, fertilization, and watering frequency on the cyanobacterial growth and its physiological characteristics through inoculating BSCs on a semiarid degraded soil. The authors found that, 6 months after the inoculation, the highest rates of nitrogen fixation, the net CO_2 exchange rate and chlorophyll *a* content occurred in biological crusts with the combination of slurry, composted sewage sludge, and watered five times per week. However, the high watering frequency resulted in lower diversity in the cyanobacterial communities. Wu et al. [3] reported that many factors including organic matter content, soil water content, total N, total P, available P, available K, pH, electrical conductivity, and total salt content significantly increased the quantities of microorganisms were, and so the concentrations of catalase, urease, phosphatase, and alkaline phosphatase did. During the dehydration of *Microcleus vaginatus*, photosynthesis fell during the process of hydration, adding some matter, such as K^+, Ca^{2+}, amylase (EPS), which were beneficial to the development and colonization of algae [10]. Bowker et al. [49] tested whether or not Mn limits photosynthesis and growth in *Collema tenax*, a dominant N-fixing lichen found in BSCs worldwide. Their results showed no evidence of such and even found that the addition of other nutrients, such as P, K, and Zn, had a suppressive effect on gross photosynthesis.

From the analysis above, fast cultivation or restoration of BSCs is much more difficult than researchers expected. We suggest that soil moisture should be the first key limiting factors for BSCs' development or growth. If water supply is enough, all nutrients, light, and temperature etc. perhaps influence their formation potentially. To achieve fast restoration of BSCs, very different external environment might be required with different dominated organism composition. Only through deep going study, the optimal environment to grow can be got and fast restoration or cultivation will be realized by creating an appropriate condition.

2.3 Responses to disturbance

Disturbance is a primary cause of spatial heterogeneity in ecosystems. It affects the composition and structure of ecosystems [50], and influences competition in the environment and substrate and resource availability [51]. Many disturbances including human activity, climate change, fire, and exotic species invasion cause extremely vulnerable response of BSCs [52–54]. Many anthropogenic activities greatly influence the presence, composition of BSCs, altering nutrient cycling and soils' development, and consequently result in a decrease of crust cover, water holding capacity, soil stability, and an increase of soil loss and soil albedo [55–59]. Belnap et al. [60] found that both raking and vehicular disturbance do not reduce chlorophyll *a* content in the surface crust after 9 months unless surface materials was removed entirely (scalping treatment). However, nitrogenase activity reduced significantly in all treatments, but a greater decline in cold deserts compared with hot deserts [61]. The disturbance in BSCs changed nutrient cycles such as reduction and decomposition rates of C and N inputs [57, 62]. On the other hand, C and N losses could increase sharply once BSCs was disturbed in water or wind erosion region [58, 63]. Belnap and Eldridge [55] argue that frequently disturbed soils only support large filamentous cyanobacteria, as later successional species are not able to develop, thus limiting microbial diversity and altering crust functioning. Soil surface disturbances convert species-rich BSCs, which are dominated by late successional cyanobacteria and lichens, to species-poor crusts dominated by early successional cyanobacteria. Zhang et al. [64] collected intact crust samples, allowed them to recover for 1 year, and then created five levels of disturbance: no disturbance (intact crusts), light disturbance (disturbance of 10 and 20% of the total area), moderate disturbance (40% disturbance), and severe disturbance (80% disturbance). Their results showed that the ability of disturbed soil crusts to resist wind erosion significantly decreased compared with shifting sand. The tunnel experiment showed the similar results. For example, threshold friction velocities for microbiotic crusts were inverse to the disturbance levels; e.g., wind erosion rates for sandy soil with 0% crust cover was about 46 times the soil with 90% crust cover at wind velocities of $18\ m\ s^{-1}$. The reduction of trampling on the soil eventually results in the re-establishment of BSCs and their associated organisms, and ultimately leads to lower levels of wind erosion. The acceleration or reduction of soil erosion in arid landscapes is primarily an outcome of management practices [50]. The continuous physical damage leads to crusts eventual demise and simultaneously deterioration of soil function. Once disturbed, BSCs will show a slow recovery process, usually ranging from years to decades [60]. A recent study showed that covers of both lichens and mosses can increase dramatically over short time periods, often increasing from just above 0% cover to as high as 9% cover in only 6 months [65]. A study conducted in Horqin sand land showed that the flowing sand dune in most natural and artificial vegetation sites was covered with BSCs after 15 years of enclosure protection and vegetation establishment, and the degree of coverage of the crust ranged from 50 to 80%, with a thickness of 1–2 cm [66]. Thomas and Dougill [67] found that crusts can recover quickly from disturbances, with a nearly complete surface crust cover forming within 15 months of disturbance in the Game Reserve and Wildlife Management Zone. Crust development is restricted by burial by wind-blown sediments and by raindrop impacts [67].

The manner and intensity with which disturbances are applied exert important impacts on BSCs. The relative level of disturbance affects the total cyanobacterial crust cover at each site, with more disturbed locations having the lowest crust cover [68]. In southwestern Germany, comparative study between weak (raked) and strong (completely removed) disturbance showed that ruderalization was mainly caused by strong disturbance, and weak one did not impact the number of vascular plant species [69]. Prasse and Bornkamm [70] reported the similar research in Israel, crust cover significantly decreased under weak and especially strong disturbance over 1 year. After 2 years, reduction of total species numbers of phanerogams and N were observed.

Heavy livestock grazing detrimentally impact on the cover, abundance, and composition of BSCs [71]. The number of cattle tracks and dung pats within a 2-m wide transect were quantified and used to provide a livestock disturbance index based on the method of Perkins and Thomas [72]. According to observations by Belnap and Eldridge [55], the resistance of BSCs to mechanical disturbances by trampling are in the following order: moss<lichen<cyanobacteria, which was confirmed by recent studies showing that lichen crust was more resistant to grazing than moss cover [73] and that cyanobacteria eventually replaced lichens and mosses in response to grazing [65]. Compared to the light-colored crusts, covers of dark-colored BSCs in exclosures increased much more significantly after the rainy season because they can better take advantage of precipitation under grazed conditions [74]. Past grazing may be responsible for declines in the species richness of both mosses and lichens and declines in cover of lichens [65]. Studies of BSCs in other regions have demonstrated dramatic responses to grazing treatments, likely because of environmental constraints in those regions. The magnitude of change in grazing removal depends on the developmental stage of the cyanobacterial BSCs, season, and grazing pressure, and is not linear nor unidirectional [74]. BSCs are more susceptible to disturbance when dry. Therefore, the lack of grazing at a time when trampling is detrimental to the crusts could also be a major factor that promotes similarity in crust cover and species richness inside and outside exclosures. Muscha and Hild [73], e.g., found that (32–45) years of grazing removal did increase soil lichen cover but increased moss cover inside exclosures. The maintenance of functioning BSCs critically determined the resilience of semi-arid pastoral systems to grazing-induced disturbance [55]. In south-western Queensland, Australia, Williams et al. [75] found that excessive damage by stock trampling immediately reduces crusts capacity to recover after drought, which may be exacerbated by the changes in the severity or intensity of drought. Trampling-induced disturbance of BSCs not only reduces soil stability but change the water and nutrient movement, eventually, spatial heterogeneity and loss in ecosystem function were leaded [76]. Another study indicated that a large seed bank present in the crust layer and top soil because its promotion to incorporation of seeds, and while disturbances happened, soil seed bank will be activated [69].

Climate change is likely to further exacerbate the conversion of later successional to early successional crusts. Increasing summer temperatures have been linked to a dramatic decline in the abundance and physiological functioning of the later successional lichen *Collema* and the cyanobacteria *Nostoc* and *Scytonema* [77]. Increased summer precipitation has been linked to a decline in the cover and physiological performance of *Collema* on both the Colorado Plateau [78] and the Mojave Desert [79]. Ford et al. [80] proposed that the reestablishment of periodic fires is fundamental to the ecological restoration of grasslands; therefore, the appropriate fire season and fire effects on ecosystem components must be determined prior to the use of large-scale fires as a management tool. Ford and Johnson [81] examined the effects of the fire season on two plant life forms in short grass steppe, non-vascular BSCs, and vascular perennial grasses in the Great Plains short grass steppe in New Mexico. Their results showed that burning during the dormant-season had little effects on grass cover, but decreased nitrogen fixation and reduced chlorophyll *a* content in crusts. Growing-season fires negatively impacted grass cover, but reduced the impact of fires on soil crusts. Some study results indicated that both disturbance and irrigation treatments caused greater variance in lichen cover because cyanobacteria was strongly positive with rainfall in the undisturbed Mojave Desert systems [82]. Increasing summer monsoon could reduce lichen cover, consequently caused a series of secondary effects such as soil stabilization, soil nitrogen, and carbon decreasing, because excess hydration and desiccation, mainly occurring with increased summer rainfall, negatively impacted CO_2 fixation in the cyano-lichen *Collema tenax* [83]. Litter or sediment cover inhibit BSCs recovery and decrease BSCs survival rates because of their physical damage and the lack of light [43, 84]. Potential movements of sediment and litter may have important implications on the spatial dynamics of BSC cover, soil erosion, and soil fertility [71]. Jia et al. [85] evaluated the effects of sand burial followed by simulated precipitation on CO_2 exchange and growth of four types crust collected from the Tengger Desert in Northern China. Their results suggested that sand burial restrict crusts succession, and pointed out that sand-binding measurements for preventing from desertification is necessary to mitigate the negative impact of sand burial on crusts. A recent research report by Scott et al. [86] showed that within lichen-dominated BSCs, there exists a much higher level of diversity of fungi than that previously determined for cyanobacteria-dominated crusts and that fungi contribute less biomass and are less diverse than their bacterial counterparts. Fungal diversity in lichen-dominated BSCs is negatively correlated, while disturbance is positively correlated, with crust cover.

While disturbances have negative effects on BSCs, causing slow regeneration and nitrogen and carbon values to drop down to levels far below normal, they also significantly facilitate seedling establishment [87]. Disturbance measurements must be performed because BSCs could inhibit soil water infiltration, accelerate evaporation, waste limited soil water in semi-arid regions, and prevent ecological restoration. For the successful coexistence of crust organisms and higher plants, the presence of the crust, as well as some intermediate, small-scale disturbance regimes, seems to be necessary in nutrient-poor environments. Criteria for the selection of the appropriate disturbance and determination of its degree could be addressed in future research.

3 Potential prospects

In summary, BSCs directly affect many ecological processes, including rainfall infiltration, soil erosion, nutrient cycling, seed germination, and biodiversity, among others; they also play important ecological functions in the evolution of soil–water–plant systems in arid areas. The formation of BSCs has spatial heterogeneity and development complexity. While BSCs can prevent erosion, they can also promote evaporation, restrain infiltration, reduce soil moisture, and make other negative impacts.

Future research on BSCs could include the following aspects: (1) Understand the roles of BSCs in carbon and nitrogen fixation in the micro-scale (block), monitor their distribution patterns in the macro-scale (region) by remote sensing technology, and evaluate the roles of carbon and nitrogen fixation in the whole ecological system. Few researchers consider the contributions of BSCs to carbon fixation and respiration in the carbon cycle in desert systems. Despite the fact that the instantaneous photosynthesis of BSCs is lower than that of vascular plants, they have high coverage and importance. Thus, studying the potential role of BSCs in carbon and nitrogen fixation and evaluating their roles in carbon and nitrogen "sourcing and collection" in desert by remote sensing technology is recommended. (2) Study the artificial cultivation of BSCs and implement engineering propagation and application of artificial BSCs. The artificial cultivation and rapid propagation of BSCs are effective methods that can improve the ecological functions of BSCs, rapidly achieve erosion control, and develop ecological environments. Researchers have suggested that producing artificial BSCs over a short period of time is theoretically feasible by indoor culture, inoculation and spraying in the field. However, obtaining artificial BSCs presents significant technical difficulties; thus, enhancements in the related research are imperative.

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