Abstract: Biological soil crusts (biocrusts hereafter) cover a substantial proportion of dryland ecosystem and play crucial roles in ecological processes such as biogeochemical cycles, water distribution and soil erosion. Consequently, studying the spatial distribution of biocrusts holds great significance for drylands, which is still lacking, especially in a global scale. This study aimed to stimulate global-scale investigations of biocrusts distribution by introducing three major approaches: spectral characterization indices, dynamic vegetation models, and geospatial models, while discussing their applicability. Then, we summarized present understandings of biocrusts distribution. Finally, to further advance this field, we proposed several potential research topics and aspects, including building standardized database of biocrusts, enhancing non-vascular vegetation dynamic models, integrating multi-sensor monitoring, making full use of machine learning, and focusing on regional research co-development. This work is supposed to significantly contribute to mapping biocrusts distribution, and thereby to advance our understandings of dryland ecosystem management and restoration.

Key words: biological soil crusts; distribution; drylands; global scales; regional scales

1. Introduction

Biological soil crusts (biocrusts hereafter) are continuous complexes that live in the topsoil,
which are formed by different proportions of photosynthetic autotrophic (e.g. cyanobacteria, algae, lichens, mosses) and heterotrophic (e.g. bacteria, fungi, archaea) organisms colloidal with soil particles, usually with a thickness of a few millimeters to a few centimeters (Weber et al., 2022). They are able to occupy a wide ecological niche in the water-limited, nutrient-poor and hostile environments, especially in arid and semi-arid areas characterized by low ratios of precipitation to potential evaporation (0.05-0.5 mm/mm) (Read et al., 2014; Pravalie, 2016; Weber et al., 2016), covering approximately 11% of the global land area (Porada et al., 2019).

As vital components of dryland ecosystems, biocrusts fulfill essential ecological functions. They contribute to stabilizing the soil surface and improving soil permeability and water-holding capacity within the upper top centimeters (Gao et al., 2017; Shi et al., 2023; Sun et al., 2023). By participating in a suite of biogeochemical cycles, biocrusts contributed 15% of terrestrial net primary productivity and 40-85% of biological nitrogen fixation (Elbert et al., 2012; Rodriguez-Caballero et al., 2018). They also impact ecohydrological processes by altering soil microclimate and redistributing soil water (Tucker et al., 2017; Kidron et al., 2022). Moreover, biocrusts influence seed capture and soil seed banks (KrÖPfl et al., 2022), thereby mediating plant growth and community assembly (Havrilla & Barger, 2018; Song et al., 2022). The extent and magnitude of these ecological functions and services depend on the spatial distribution of biocrusts. Therefore, it is crucial to understand their distribution.

Despite the significance of biocrusts, previous studies have primarily focused on carbon and nitrogen mechanisms (Morillas & Gallardo, 2015; Hu et al., 2019), interspecific interactions and biocrusts biodiversity (Munoz-Martin et al., 2019; Machado de Lima et al., 2021), rather than their spatial distribution, particularly at the global scale. Consequently, a systematic and accurate assessment of biocrusts’ ecological roles remains challenging. In this study, we firstly sorted out the main research methods for studying biocrusts distribution (section 1), then reviewed the existing knowledge (section 2), and finally proposed strategies to advance the study of large-scale biocrusts distribution (section 3). This work is expected to deepen our understandings of dryland ecosystem processes, and to provide a scientific basis for dryland ecosystem conservation and their responses to global change.

2. Research Methods
In the study of biocrusts distribution, three methods are commonly used: spectral characterization, vegetation dynamic modeling, and geospatial modeling. This section provides an overview of these methods, including their basic principles, adaptability, and limitations.

2.1 Spectral characterization index

The first is spectral characterization method. Advances in remote sensing and geo-information technologies have made spectroscopy one of the most powerful approaches for determining the distribution features. Differences in absorption or reflection of specific wavelengths of different ground covers can effectively identify soil surface objects (Rodriguez-Caballero et al., 2015). By identifying biocrust-specific bands from the reflectance spectral images (Karnieli et al., 1999), it is possible to construct a presence-absence map of biocrusts distribution (Fig. 1a).

The crust index (CI) and biological soil crust index (BSCI) are two of spectral characterization indexes and have been successfully applied in Negev Desert (cyanobacteria-dominated) (Karnieli, 1997; Noy et al., 2021) and Gurbantunggut Desert (lichen-dominated) (Chen et al., 2005). For such indicators, it is critical to determine the threshold of spectral bands that represent biocrusts. For instance, at an aerosol optical depth of 0.2, the BSCI ranges from 4.13 to 6.23, and narrows to 4.58-5.69 with increasingly poor atmospheric conditions. Overly strict or loose threshold ranges can easily lead to biocrusts omission or misidentification. In order to improve the accuracy of biocrusts identification, some researchers took advantage of the hyperspectral sensor’s continuous waveband, and created Continuum Removal Crust Identification Algorithm (CRCIA) (Weber et al., 2008; Chamizo et al., 2012). Baxter et al. (2021) innovatively applied the random forest algorithm to spectral feature classification, and achieved an accuracy of 78.5% in biocrusts recognition. Another two indexes, i.e., the sandy land ratio crust index (SRCI) and the desert ratio crust index (DRCI), were also introduced by taking into account the differences between sandy land (vegetation cover FVC <20%) and desert environments, which could improve the accuracy of the mapping by ~6% (Wang et al., 2022).

The spectral characterization method is easy to use, and thus, facilitates the access to continuous long-term dynamics of biocrusts distribution. However, mosses and vascular plants
are generally mixed up in this case because their reflectance characteristics are close to each other in all wavelengths especially when mosses are wet, which makes them indistinguishable (Fang et al., 2015). Therefore, spectral characterization method is mainly applicable to situations where biocrusts cover is >30% and plants cover is <10% (Beaugendre et al., 2017). It should be noted that, the existing indexes mostly correspond to biocrusts cover consisting of specific dominant groups in specific environments, which cannot be directly extrapolated to areas with high heterogeneous environments (Table 1). Wetting or disturbance may also lead to large fluctuations in reflectance of different land types and interfere with biocrusts distribution monitoring (Rodriguez-Caballero et al., 2015; Weber & Hill, 2016).

2.2 Dynamic global vegetation models (DGVMs)

Dynamic global vegetation model is another major method to obtain vegetation cover (Deng et al., 2022). Dynamic global vegetation model mainly focuses on simulating the biogeochemical processes (e.g. carbon, water cycles), metabolic and hydrological processes of organisms (Lenton et al., 2016; Porada et al., 2017). The method possesses significant advantages to map global biocrusts distribution because its assumptions have clear biological implications (Cuddington et al., 2013). To use DGVMs, the following procedures need to be taken. The first step is building model framework, simulating important and interesting processes such as biocrusts growth and death, nutrient cycle, and water cycle (Porada et al., 2013). So far, there is only one dynamic global vegetation model targeting at biocrusts - the Lichen and Bryophyte Model (LiBry) (Fig. 1b) (Porada et al., 2013, 2019). The second step is parameterization. Generally, literature and open databases are used to assign physiological strategies for different types of biocrust, such as photosynthesis, respiration and nitrogen emission under the influence of temperature, precipitation, radiation, biological water saturation, etc. The third step is importing environmental data into the model to obtain the biocrusts cover at grid points over a specific study region. At last, the results are tuned and validated against observation data of biocrusts distribution (obtained by literature comparison and local field observations), and thereby biocrusts distribution map is produced. Such simulation models heavily relies on the differences in the physicochemical properties of metabolic activity of organisms (Quillet et al., 2010). Inevitably, this kind of study requires...
large observation data and extensive human intervention, yet the accuracy of the study cannot
be well guaranteed at present (Table 1).

2.3 Geospatial models

Directly relating vegetation presence or cover to environmental data instead of indirectly
via biological processes in DGVMs is another important way to obtain biocrust’s distribution
(Skidmore et al., 2011; Fischer & Subbotina, 2014; Beaugendre et al., 2017). Classic statistical
models can serve for this purpose. However, they still require comprehensive expert knowledge
of how environmental factors affect biocrusts (Pearce et al., 2001), which is hard to get and
prone to be biased. Geospatial models which integrating machine learning tools with field
survey data and remote sensing data is supposed to hold the most promise (Crego et al., 2022).

Geospatial model is also known as species distribution model or ecological niche model
(Jiménez-Valverde et al., 2008; Soberon & Nakamura, 2009; Brown & Anderson, 2014). The
procedures of how to use geospatial modelling are illustrated in Figure 1c (Rodriguez-Caballero
et al., 2018): 1) extracting environmental data for the sites where biocrusts observation data are
reported, 2) importing the extracted environmental data into the machine learning framework
and obtaining the relationship between biocrusts distribution and environmental variables
through a specific algorithm (e.g., decision tree algorithms, Bayesian algorithms, artificial
neural networks, etc.), 3) simulating biocrusts distribution by extrapolating to the whole study
region using the constructed relationships. Nevertheless, geospatial models are black-boxes and
largely non-interpretable, and thus, less capable of capturing key mechanisms behind
phenomenon, which may limit its applications. One should note that, to avoid confounding
model predictions, inclusion of environmental factors should be based on relevance of
environmental factors to biocrusts, and still need expert knowledge to a certain degree
(Mäkinen et al., 2022). Supplied with sufficient computing power and observation data of
biocrust distribution, and suitable environmental, geospatial models are supposed to able to
predict biocrust distribution accurately. Therefore, geospatial modelling is considered to be one
of the most proper methods available (Table 1).
Fig. 1 Illuminations of applying spectral characterization method (a), vegetation dynamics model (b) and geospatial model (c) in biocrusts distribution study. See main text for more detailed introduction to these methods.

Table 1 Comparison among the three main types of methods to predict biocrusts distribution

<table>
<thead>
<tr>
<th>Spectral characteristic index</th>
<th>Vegetation dynamics model</th>
<th>Geospatial model</th>
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<tbody>
<tr>
<td>Principle</td>
<td>Differences in wavelength reflectance of surface features</td>
<td>Differences in the physiological processes of different biocrusts types</td>
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<tr>
<td>Advantages</td>
<td>Convenience and ease of use</td>
<td>Clear ecological significance</td>
</tr>
<tr>
<td>Disadvantages</td>
<td>Reflectivity is affected by climate change, disturbances; Mosses and vascular plants have similar reflectance characteristics; The results only show the presence or absence</td>
<td>Experience-based promotion with significant human intervention; Experiments need to be supported by big data</td>
</tr>
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</table>
of biocrusts, without coverage

<table>
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<tr>
<th>Applicable scales</th>
<th>Regional scale (Desert and sandy land with &lt;20% vegetation cover)</th>
<th>Regional scale</th>
<th>Regional scale</th>
</tr>
</thead>
</table>

3. What have we known?

Since 1990, studies on the distribution of biocrusts has been continuously increasing. Biocrusts spatial distribution has gradually received attention from all over the world, in particular the countries with extensive dryland areas such as China, United States, Spain, United Kingdom, Germany, Australia and Israel. A group of ecologists, represented by Fernando Maestre, David Eldridge, Matthew Bowker, Emilio Rodriguez-Caballero and others, have been have been actively involved in the field (Fig. 2).

![Fig. 2 Representative authors associated frameworks for biocrusts distribution studies (1990 to 2022). The time series is the average time of the year of publication, e.g., if the number of articles is 2 in 2004 and 8 in 2019, the node in this figure shows the year as (2004 x 2 + 2019 x 8)/10 = 2016. The database is Web of Science, TS = ("biogenic crust*" OR "biological crust*"
OR "biological soil crust*" OR "biocrust*" OR "microphytic crust*" OR "microbiotic crust*"
OR "cyanobacterial*" OR "algal*" OR "lichen*" OR "moss*" OR "biotic crust*") AND
("mapping*" OR "distribution*" OR "spatial pattern") AND ("dryland" OR “hyper*arid*” OR

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“arid*” OR “semi*arid*” OR “dry subhumid*”), with research interests in Environmental Sciences/Ecology and a total of 700 papers.

3.1 Local-regional scales

At local-regional scales, numerous studies have provided valuable insights into the distribution patterns of biocrusts in different regions around the world. In the Mojave Desert, biocrusts distribution was closely related to geological age, surface stability, topography, and dust transport (Miller et al., 2004), lichen, moss, and dark algal crusts patchily distributed on its northeastern slopes, averaging 8% cover, though in some bar and shrub zones, the cover could be as high as 16% (Pietrasiak et al., 2014). In the Colorado Plateau, highly heterogeneous soil matrix determined the fragmented biocrusts distribution of different types and the wide disparity in relative abundance and cover (Reynolds et al., 2006; Steven et al., 2013). Collier et al. (2022) trained drone imagery in the Hawaiian region using timely data collected by cameras and then successfully mapped watershed-scale biocrusts distribution, predicting cover of ~15-23%. In the Gurbantunggut Desert, biocrusts cover 28.7% of the area, with a high and uniform biocrusts cover in the southern part of the desert and a scattered distribution of biocrusts in other areas (Chen et al., 2005; Zhang et al., 2007). Does plot size have an effect on the variation in biocrusts cover? RGB image-based biocrusts monitoring on the Loess Plateau showed that variability in biocrusts cover decreased logarithmically with increasing plot size until a critical size of 1m² after which biocrusts cover remained approximately constant (Wang et al., 2022). In Qatar, 26% of the country is covered by biocrusts, with cyanobacterial biocrusts cover showing a decreasing trend from north-east to south-west (Richer et al., 2012). In the northern Negev, the distribution of biocrusts is well developed, by simulating the spectral characteristics of the different components of biocrusts after seasonal precipitation, especially the chlorophyll absorption characteristics, it was found that the greening of the biocrusts was obvious, which could provide a basis for the subsequent tracking of their distribution (Panigada et al., 2019). At the Sinai Peninsula (Egypt) – Negev desert (Israel) border, the distribution dynamics of cyanobacterial biocrusts over a 31-year period has now been obtained from the crust index (Noy et al., 2021). Filamentous cyanobacteria grow in the African Sahara (Issa et al., 1999), where statistical models of combined environmental indicators showed biocrusts
cover of 1 ~ 48% and 0 ~ 65% in Banizoumbou and Tamou respectively (Beaugendre et al., 2017). Recent research predicted that under future scenarios of reduced precipitation, increased temperature and aridity in southwest Africa, the biocrusts cover will decrease ~25% by the end of the century and the communities may shift towards early cyanobacterial biocrusts (Rodríguez-Caballero et al., 2022).

### 3.2 Global scale

To date, there are only two global-scale studies of biocrusts distribution. Porada et al. (2013) focused on CO₂ diffusion rates and photosynthetic processes under dynamic water content saturation in dryland biocrusts. By parameterizing long-term climate and disturbance intervals and averaging simulation results for the past 20 years for each grid point, they estimated that biocrusts cover 11% of global terrestrial land surface (Porada et al., 2019). Their results also showed that the light and dark cyanobacteria were widely distributed in deserts, savannas, grasslands and Mediterranean woodlands at low latitudes, and increase to some extent with increasing dryness, while mosses were mostly distributed in middle and high latitudes and polar regions (Fig. 3a). Rodriguez-Caballero et al. (2018) fitted biocrusts presence-only data to the bioclimate, soil properties, land use data, and then extrapolated to a continuous global distribution of biocrusts using the Maxent model. This work assessed the total area covered by biocrusts to be 1.79×10⁷ km², 12.2% of global drylands, in other words, biocrusts cover was 1.2% larger compared to the area predicted by Porada et al., (2019) (Fig. 3b). After comparing two maps of global biocrusts distribution, biocrust distribution is generally consistent in the large deserts of Asia, western America, Europe and Oceania, while some semi-arid regions, such as the northern and southern margins of African Sahara Desert, South Asia and central North America, have significantly higher biocrusts cover in the latter projection of Rodriguez-Caballero et al. (2018).
Fig. 3 Maps of the results of global biocrust distribution. a, prediction based on vegetation dynamic model (Porada et al., 2019). b, prediction based on geospatial model (Rodriguez-Caballero et al., 2018).

3.3 Influencing factors of biocrusts distribution

What factors influence the global distribution of biocrusts? In general, precipitation is considered to be critical in determining the distribution of biocrusts (Eldridge & Tozer, 1997). Increased precipitation could lead to higher levels of lichen and moss, while algal cover may first increase and then decrease (Marsh et al., 2006; Budel et al., 2009; Zhao et al., 2014). It should be noted that, precipitation can also promote the growth of vascular plants, and the continuous and high cover of vascular plants and litterfall will limit the space available to biocrusts (Bowker et al., 2005). In addition to the total amount of precipitation, the seasonality and frequency of precipitation cannot be ignored (Budel et al., 2009). Winter precipitation and/or smaller rain events benefit biocrusts most (Chamizo et al., 2016; Jia et al., 2019).

Whereas, it has been experimentally proven that short-term and frequent light rain events killed moss biocrusts in the Colorado Plateau, USA (Reed et al., 2012). Non-precipitation water input is another important water resource type. The Namib Desert receives little rainfall, but lichens and moss biocrusts can reach a relatively high cover (~70%) (Budel et al., 2009). This is because local water vapour tends to condense into fog or dew, which facilitates the survival of three-dimensional species (such as leafy lichens) by trapping air moisture (Kidron, 2019; Eldridge et al., 2020; Li et al., 2021). The relatively high soil temperature also creates an environment of high evaporation that impedes biocrusts colonization (Garcia-Pichel et al., 2013). In addition to the effects of the current climate, researches began to study the effects of climate change in the dryland on the structure of biocrusts communities (Ferrenberg et al., 2015), including climatic legacy effects. Changes in temperature and precipitation over the last 20,000 years have been found to indirectly affect the distribution and relative species richness of biocrusts through changing vegetation cover and soil pH (Eldridge & Delgado-Baquerizo, 2019).

The distribution of biocrusts at global scale is also correlated with biogeographic isolation, soil texture and disturbance (Rodriguez-Caballero et al., 2018; Sosa-Quintero et al., 2022).
Strong spatial heterogeneity accompanied with spatial distance can set up barriers to the dispersal of propagules (spores, fungal bodies) (Garcia-Pichel et al., 2013). For a long time, it was commonly believed that finer soils benefit biocrusts growth (Williams et al., 2013; Belnap et al., 2014). However, this has been challenged by some scientists. For example, Kidron (2018) believed that soils with high dust or fine grains were not a necessary condition for biocrusts distribution. Another study had shown that the soil parent material determines the degree of surface weathering and the water-holding capacity of the soil, thus indirectly changing the distribution of biocrusts (Bowker & Belnap, 2008). Gypsum or calcareous soils tend to develop mosses and lichens (Elbert et al., 2012), sandy soils tend to develop cyanobacteria (Root & McCune, 2012). As grassland is one major lifeform in dryland ecosystems, it is of great significance to explore the effects of fire events on biocrusts distribution (Palmer et al., 2022). Fire-induced soil warming will alter the resource allocation and dynamic growth mechanisms between biocrusts and vascular plants (McCann et al., 2021), which may cause a reduction in species richness and cover of biocrusts, especially cyanobacteria and algae (Abella et al., 2020; Brianne et al., 2020). Condon and Pyke (2018) showed that moss cover increases with time after fire, with no significant change in lichen cover. Finally, the intensification of human disturbance, the continued development of land and the intensification of livestock trampling generally harm biocrusts (Rodriguez-Caballero et al., 2022). The effects of soil stability (Stovall et al., 2022), soil fertility (Bowker et al., 2006), vegetation cover (Seitz et al., 2017), topography (Su et al., 2020) and solar radiation (Durham et al., 2018) on the distribution of biocrusts are relatively pronounced at local, landscape and smaller scales, see Controls on distribution patterns of biological soil crusts at micro- to global Scales for details (Bowker et al., 2016).

4. Challenges and perspectives

Biocrusts are very important for dryland ecosystems, and thus, biocrust distribution gradually becomes a hot spot since the turn of the century. The methods are shifting from traditional observational and controlled experiments to combining methods across ecology, biology, geology and computer science disciplines. However, high-precision biocrusts distribution data across geographic units are still lacking, and research methods are still limited.
To further advance studies of biocrusts distribution, we raise the following aspects.

4.1 Building standardized biocrusts database

Standardized and specialized biocrusts database consisting of the same data items (main types and cover of biocrusts, latitude, longitude and cover, etc.) and using the same inclusion criteria, which is an important infrastructure for mapping global biocrusts distribution, serving as the benchmark to train and validate spectral characteristics, DGVM, and geospatial models (Engel et al., 2023). Due to the difficulty of conducting field surveys worldwide, compiling biocrusts data from the published literatures or other channels is the major approach (Fig. 4).

Several studies had been conducted to collect data from literatures, obtained 900-1000 sample points of biocrusts presence and 584 sample points of biocrusts cover in global dryland (Rodriguez-Caballero et al., 2018; Havrilla et al., 2019; Chen et al., 2020; Eldridge et al., 2020). However, compiling from literatures largely comes to its limitation and is still far from building a standardized and specialized biocrusts database. While open databases are not specialized to biocrusts, some of them may be important additions. For example, the biodiversity and specimen datasets such as GBIF and the Atlas of Living Australia (Belbin & Williams, 2015; Garcia-Roselló et al., 2015), which contain a large amount of information on species, of course including mosses and lichens (Table 2), which can contain hundreds or even thousands of entries of biocrusts occurrence or cover. Similarly, global, national and regional plant flora may significantly contribute to building the standardized and specialized biocrusts database. For example, sPlot includes ~2 millions of vegetation plot data (Sabatini et al., 2021), and the European Vegetation Archive (EVA) also possesses 1.6 million entries over globe or Europe (Chytrý et al., 2016). Regional datasets like Environmental Monitoring of arid and Semiarid Regions (MARAS) surveyed 426 sites (up to September 2020), and provided regular access to 624.50 km² of rangeland vegetation spatial patterns, species diversity data, soil functional indices, climatic data and landscape photographs in Patagonia region straddling Argentina and Chile (Oliva et al., 2020). In addition to above channels, an increasing number of amateurs are getting involved in science through species identification apps with clean, easy-to-use apps, contributing significantly to global species information entries. The citizen science project iNaturalist is a very good example (Wolf et al., 2022). Furthermore, when collecting and...
collating data from the non-academic sources, the combination of web crawlers and text analysis can help in obtaining biocrusts data and solving key ecological issues. In addition, high resolution sensors have been found to be successful in monitoring lichens and mosses (Blanco-Sacristan et al., 2021) and the release of such products is something important to look out for in the future.

![GBIF Distribution](image1)

![MARAS Monitoring](image2)

![PROBA V_LC100 Distribution](image3)

**Table 2** References for biocrusts database expansion channels

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**Data type**: Biodiversity data, Survey data, Landcover data

**Coverage**: Worldwide, Argentina and Chile, All

**Presence**: ✓

**Coverage**: —, --

There are only two DGVMs applicable to non-vascular organisms – LiBry and ECHAM6-HAM2-BIOCRUST (Rodriguez-Caballero et al., 2022). Their performances still need to be improved. Considering spatial self-organization of non-vascular organisms (Gassmann et al., 2000), the effects of fire (Thonicke et al., 2001), vegetation-environment feedback processes (Quillet et al., 2010), functional traits (Boulangeat et al., 2012), intraspecific-interspecific interactions (Boulangeat et al., 2014) and seasonal dynamics in current and/or new DGVMs can be future directions. In addition, how the physical properties, photosynthetic capacity, carbon and nitrogen allocation of biocrusts change along environmental gradient are complex and context-dependent, which should be incorporated into DGVMs (Fatichi et al., 2019).

Spatial-explicit DGVMs may be one key to effectively improving the accuracy of simulations in future studies, but are data-consuming. Also, biocrusts are significantly influenced by hydrological processes and vice versa (Whitney et al., 2017; Chen et al., 2018), while ecohydrological models based on hydrological processes are rarely connected to global biocrusts distribution predictions. Jia et al. (2019) tried to incorporate biocrusts cover as a system state variable in an ecohydrological model and investigated biocrusts cover under rainfall gradient. If fed with global data of environmental variables (mainly hydrological relevant ones), ecohydrological models may be a new approach to predicting biocrusts distribution at global scales.

4.3 Integrated application of high-quality sensors

Spectral characterization method lies on the differences in spectral reflectance of biocrusts and other land types at different wavelengths, and thus, the accuracy of the results depends on the quality of the sensors. However, previous studies have often used a single sensor with constant band intervals for distinguishing biocrusts, which may result in missed spectral feature identification of land types (Chamizo et al., 2012). If the biocrusts index can be constructed by combining and comparing the full-band spectral data from multiple terrestrial sensors and infrared cameras and other devices, the errors will be reduced to a certain extent, thus improving the classification accuracy. In addition, the unique advantages of hyperspectral data with large data volume and narrow band allow it to be used to combine with observation data to co-develop new biocrusts discrimination standard. If further estimation of biocrusts cover can be
achieved on this basis, it will be an important contribution to the study of large scale biocrusts 
distribution (Rodriguez-Caballero et al., 2017).

4.4 Making full use of machine learning

Machine learning can be combined with remote sensing products to find complex features 
from big data to predict global biocrust distribution (Collier et al., 2022). This data-driven 
approach has powerful predictive capabilities, especially for mapping species distribution, and 
can largely circumvent the mistakes of missing or misidentifying biocrusts caused by traditional 
methods (relying on field measurements to determine threshold ranges) (Wang et al., 2022). In 
the remote sensing image classification problem, mature machine learning algorithms include 
support vector machines, single decision trees, random forests, artificial neural networks, etc. 
(Yu et al., 2020). Ensemble models combining multiple algorithms have been widely used in 
the field of species distribution, but relatively few applications exist in field of biocrusts 
prediction (Rodriguez-Caballero et al., 2018). In the future, using machine learning to find 
parameters for dynamic models of biocrusts, which may be one of the most promising method 
to predict biocrusts distribution (Perry et al., 2022).

4.5 Regional research synergy development

Spatially, the study areas that have been conducted are relatively concentrated in countries 
such as China, USA, Spain, Australia and Israel. Although there are large areas of dryland 
distributed in Africa (other than South Africa), central Asia, central South America and northern 
North America, research on biocrusts in these regions are scarce. Unbalanced regional research 
efforts are one of the constraints to advancing studies of global biocrusts distribution. Therefore, 
how to coordinate and promote the common progress of regional research is an urgent issue at 
present. In addition to the drylands, the cold zones may be another important area to explore 
biocrusts distribution (Pushkareva et al., 2016). On the Tibetan Plateau, studies have 
investigated the spatial variation of different types of biocrusts communities across climatic 
gradients and their effects on soil temperature features and freezing duration (Ming et al., 2022; 
Wei et al., 2022). This urges the studies of biocrusts distribution in the alpine areas.

To sum up, as biocrusts being one of key organizing principles in drylands where 
environmental stress and climate change become increasingly severe, it is essential to explore
the global distribution of biocrusts. This study summarized three major methods of predicting biocrust distribution, sorted out the current knowledge of biocrust distribution, and made suggestions for advancing this field. The research will be an important cornerstone of related work that help conserve and restore critical areas of global drylands, and thereby for the healthy development of natural-human society.

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