Ecological and environmental explanation of microbiotic crusts on sand dune scales in the Gurbantonggut Desert, Xinjiang*

CHEN Yaning, LI Weihong, ZHOU Zhibing and LIU Jiazhen**

(Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, Urumqi 830011, China)

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Abstract Results obtained from the field investigation and the analysis in laboratory show that many species of microbiotic crusts of lichens, mosses and algae develop extensively in the Gurbantonggut Desert, Xinjiang. The formation, species and distribution are closely related to the environmental conditions at the different positions of sand dunes. The animalcule crusts develop mainly on the mobile or semi-mobile sand surface of dune tops, the alga crusts develop mainly at the upper to middle parts of dune slopes, the lichen crusts develop at middle and lower parts of dune slopes, and the moss crusts are mainly distributed at the lower part of dune slopes and the interdune lowlands. The species, thickness and developing degree of microbiotic crusts increase from the upper part to the middle and lower parts of dune slopes and the interdune lowlands, and an obvious contrast between the microbiotic crusts and the different species of plant communities forms. The development and differentiation of microbiotic crusts at the different positions of dunes are the ecological appearance and the natural selection of synthetic adaptability of the different microbiotic crust species to the local environmental conditions, and are closely related to the ecological conditions, such as the physiochemical properties of soils and stability of topsoil texture.

Keywords: **microbiotic crust, sand dune scales, environmental explanation, the Gurbantonggut Desert.**

Microbiotic crusts are the organic complexities composed of biotic components including mosses, lichens, algae and bacilli with topsoil. Microbiotic crusts can exist in various desert habitats because of their peculiar physiological and ecological processes, and they develop extensively in all the deserts in arid and semiarid regions all over the world[1,2]. As a new study topic in environmental protection and ecological regeneration in arid areas, microbiotic crusts play an important role in the occurrence, development and control of desertification, and attract more and more attention. The study results reveal that microbiotic crusts in deserts cannot only fix sand surface of dunes, reduce soil erosion, but also have the ecological functions in changing the physiochemical properties of soils in deserts and affecting the surface hydrological process and soil nutrient circulation[3]. Microbiotic crusts could provide the conditions for the growth of vascular plants, promote the vegetation succession and the bourgeoning and growth of vascular plants, and improve the ecology[4—6].

The Junggar Basin is a typical temperate desert in the world, where the Gurbantonggut Desert, the second largest desert in China, is located in. In the desert vegetation in the basin, there are not only the typical psammophyte communities, but also the typical salt desert plant communities and large quantity of ephemeral and ephemeral-like plants. Moreover, there are plentiful species of lichens, mosses and algae, forming microbiotic crusts of 2—5 cm in thickness. Especially the coverage of microbiotic crusts can be as high as 70%—80% in the south of the Gurbantonggut Desert. Except the spermatophytes, the microbiotic crusts play an important biological role in fixing sand surface of dunes in the Gurbantonggut Desert. Therefore, the study on the microbiotic crusts in the desert is paid great attention to[7]. In this study, the occurrence of microbiotic crusts and the environmental features of developing microbiotic crusts on dune surface are researched and parsed based on the field investigation and the analyzed results in laboratory so as to reveal the formation process and distribution patterns of microbiotic crusts in sand dune scales in the Gurbantonggut Desert and further understand the ecological functions and significance of microbiotic crusts in controlling sand drift and fixing dunes in arid deserts.

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** To whom correspondence should be addressed. E-mail: chenyn@ms.xjb.ac.cn

1 The study area and sampling

1.1 The study area

The Gurbantonggut Desert is located in a zone of 44°11′—46°20′N and 84°31′—90°00′E. Its area is 4.88×10^4 km^2, in which the area of fixed and semi-fixed dunes occupies 87% of the total desert area. The strike of dunes is roughly NW-SE, most dunes are 15—20 m in height and belong to the fixed or semi-fixed dunes; the vegetation coverage on dune surface varies in a range of 15%—55%, in which the vegetation coverages on fixed dunes and semi-fixed dunes vary in ranges of 40%—55% and 15%—25% respectively. The average annual precipitation in the desert does not exceed 150 mm, it is only 70—100 mm in the hinterland of the desert, and precipitation occurs mainly in spring but less in winter. The average annual evaporation is over 2000 mm, the annual air temperature varies from 6℃ to 10℃, the extremely maximum temperature is over 40℃, and the annual accumulated temperature ⩾10℃ varies in a range of 3000—3500℃. In the psammophytes in the study area, the small semi-arbors include mainly *Haloxylon ammodendron* and *Haloxylon persicum*, the shrubs and small semi-shrubs mainly *Ephedra distachya*, *Calligonum leucocladum*, *Artemisia arenaria*, *Seriphidium terrae ~ albae*, etc.; ephemeral and ephemeral-like plants grow extensively, they include mainly *Geraniaceae sp.*, *Alyssum linifolium*, *Trigonella tenella*, *Carex physodes*, *Hypecoum parvifiorum*, *Eremurus anisopteris*, *Lappula rupestris*, *Erysimum cheiranthoides*, etc., and their average coverage can be as high as about 40% in May. Microbiotic crusts dominated by lichens are extensively distributed at the lower part of dune slopes and the interdune lowlands, in which there are also many species of animalcules, algae and mosses, their composition and distribution are different from the different environmental conditions, and they are the important biological factors in fixing sand surface except spermatophytes in the Gurbantonggut Desert.

1.2 Sampling and test of samples

The selected sampling plots are located in the southern part of the Gurbantonggut Desert where microbiotic crusts are most developed. In order to compare and analyze the occurring characteristics of microbiotic crusts at different positions of dune slopes, the species, coverage and thickness of microbiotic crusts and the vegetation distribution at the upper, middle and lower parts of dune slopes and the interdune lowlands were investigated according to the landforms and the species of microbiotic crusts. Moreover, the soil crust samples and soil samples were also collected from the soil sections of 0—20 cm in depth at the upper, middle and lower parts of dune slopes in the Gurbantonggut Desert so as to reveal the differences of microbiotic crusts over the different underlying surfaces in the desert in the Junggar Basin.

By the methods of the international soil analysis, the following physiochemical properties of soil samples were determined by different tests: soil granularity was measured by a densimeter, soil moisture content by drying method, soil organic matter content by the $K_2Cr_2O_7$ method (GB9834-88), soil total N by $CuSO_4$-Se powder diffusion method (GB7848-87), soil total P by NaOH melting- Mo Te Sc colorimetry method (GB7852-87), soil total K by NaOH melting-flaming luminosity method (GB7854-87), soil available P by 0.5 mol/L $NaHCO_3$ leaching-Mo Te Sc colorimetry method, soil available N by alkali hydrolization- diffusion method, and soil available K by 1 mol/L NH_40Ac leaching- flaming luminosity. Soil pH values were measured by a PHS-2C digital acidimeter, and the values of soil conductance by the DDS-307 conductometer. The values of soil total salt were measured with weight method, CO_3^{2-} and HCO_3^- in aqua-soluble salts in soil with double-indicator titering, the values of Cl^- with silver nitrate titering, the values of SO_4^{2-}, Ca^{2+} and Mg^{2+} with EDTA capacity measurement, and the values of K^+ and Na^+ were measured by flame photometry.

2 Results and analysis

2.1 Physiochemical properties of soils with microbiotic crusts

2.1.1 Granular characteristics of the crusted soils

The surface materials in the Gurbantonggut Desert are dominated by medium sand and finer materials, and their total proportion occupies 78.74%—94.56%. The analysis on the material composition in the Gurbantonggut Desert in Junggar Basin revealed that the granular characteristics of soils are different from different positions of landforms. The proportion of materials finer than extremely fine sand (<0.25 mm) increases gradually from the upper part of dune slopes to their middle and lower parts and the interdune lowlands. Moreover, sand sorting at the upper part of dune slopes is good, dominated by medium sand, taking up 34.43%—40.15%, while at the middle part of dune slopes, the fine sand is dominant (30.48%—31.08%), the coarse sand reduces obviously and occupies 5.68%—6.61% only. At the lower part of dune slopes and the interdune lowlands, the proportion of extremely fine sand is dominant, then that of fine sand and medium sand, and silt and clay increase obviously (over 15%). The difference of soil composition affects directly the soil porosity, soil bulk density, soil moisture content, soil osmosis, and soil cohesion. Generally, the poorer the sorting of deposits, the finer the soil grains are, the lower the soil osmosis will be[8]. The fine materials reduce possibly the soil porosity, forming a barrier for the effective osmosis, which benefits the formation and development of microbiotic crusts and the growth of plants with shallow root[9,10].

2.1.2 Change of soil moisture content

The seasonal dynamic change of topsoil moisture content in the Gurbantonggut Desert is mainly affected by rainfall and snowmelt water. The seasonal change of topsoil moisture content is significant. Soil moisture content in spring is high and changes significantly because snowcover begins to melt and rainfall is more in this season; soil moisture content in summer is reduced but is in a steady state along with temperature increase, rainfall reduction and moisture consumption by plant growth[11]. We observed that the soil moisture content in sand dune is obviously different from different positions of dune slopes and the different depths (Fig. 1). The highest soil moisture content occurs at depth of 10—20 cm at the upper part of dune slopes, but it occurs at depth of 5—10 cm at the middle part of dune slopes, and at depth of 2—5 cm at the lower part of dune slopes and the interdune lowlands. This is obviously different from that the soil moisture content increases with the increase of depth at the upper part of dune slopes. The effects of microbiotic crusts on the permeation of the limited rainfall and the soil moisture transport are very significant[12], however, the effect of microbiotic crusts on soil moisture transport is not understood yet, and there is also a divarication about the restriction or promotion of microbiotic crusts on rainwater permeation. Many ephemeral plants grow and a lot of microbiotic crusts are distributed at the lower part of dune slopes and the interdune lowlands in the Gurbantonggut Desert, and their effects on soil moisture content at different depths need to be further researched.

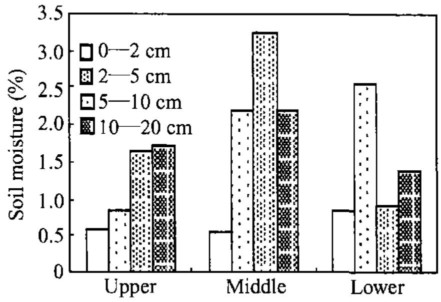

Fig. 1. Soil moisture at different parts of the sand dune.

2.1.3 Change of soil salt content and nutrient

The content of soluble salts in topsoil in the Gurbantonggut Desert is slightly lower than that in other sand deserts[12], varies in a range of 0.020%—0.032% and represents an increasing trend from the upper part to the lower part of dune slopes. The salt content in topsoil of 0—5 cm at the interdune lowlands is the highest. The change of contents of the exchangeable electropositive K^+, Ca^{++}, Mg^{++} and Na^+ in soils is very slight. However, it should be pointed out that the contents of Ca^{++} and K^+ are significantly higher than that of Mg^{++} and Na^+, in which the content of Mg^{++} is the lowest, which is possibly related to the high content of K^+. The study reveals that the increase of K^+ content can reduce the content of Mg^{++}[13]. The effect of exchangeable cation in the colloid solution of soil is different. It can affect the growth of different microbiotic crusts, especially the alga crusts.

Organic matter content in soil in the Gurbantonggut Desert is low and varies in a range of 0.078%—0.158%, which reflects the poor accumulation of organic matter in soil in the desert. The organic matter content in soil increases from the upper part of dune slopes to their middle and the interdune lowlands, being 0.112%, 0.123% and 0.158%, respectively. Wind erosion is weak at the lower part of dune slopes and the interdune lowlands, aeolian deposits are serious, the topsoil matrix is relatively stable, and snowmelt water in spring and rainfall at the interdune lowlands in summer promote the decomposition of aeolian deposits and the activity of animalcules. Moreover, microbiotic crusts are connected by hyphas and netted lichen underlay, thus, the soil granular structure is reinforced, and the soil nutrient situation is improved[14].

2.1.4 pH values and conductance of soil

pH value of soil has a certain effect on the different microbiotic crusts[15]. The pH of soil in the Gurbantonggut Desert is in alkalescence, and its values vary in a range of 8.43—8.66, in which the pH value of soil at depth of 5—15 cm is slightly higher than that at depth of 0—5 cm at the upper and middle parts of dune slopes, whereas at the lower part of dune slopes and the interdune lowlands, the pH value of topsoil at depth of 0—5 cm is higher than that at depth of 5—15 cm (Fig. 2). The pH value of soil at the lower part of dune slopes and the interdune lowlands is slightly higher than that at the upper and middle parts of dune slopes, generally, however, the difference is not remarkable, which reveals that the eluviation of soil is very limited. Moreover, the analyzed results of pH values of soil reveal that the microbiotic crusts in the Gurbantonggut Desert are in the alkaline development, in which the alkaline process of microbiotic crusts at the lower part of dune slopes and the interdune lowlands is the most significant. The conductance of soil in the Gurbantonggut Desert varies in a range of 0.051—0.074 $ms \cdot cm^{-1}$, it is high at the lower part of dune slopes and the interdune lowlands, and the conductance of topsoil at depth of 0—5 cm is higher than that at depth of 5—15 cm, and its change is similar to that of salt content and pH value of soil.

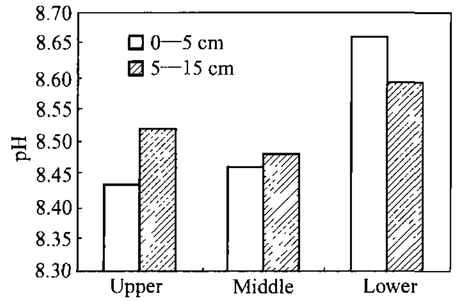

Fig. 2. pH value at different parts of sand dune.

2.2 Distribution, succession and environmental explanation of microbiotic crusts

2.2.1 Species and distribution of microbiotic crusts

There are many kinds of microbiotic crusts in the Gurbantonggut Desert in Junggar Basin, of which the most extensively distributed and developed ones are the crusts of animalcules, algae, lichens and mosses[16]. In the animalcule communities, bacilli, actinomyces and epiphytes are dominant, especially bacilli and actinomyces. The alga crusts dominated by algae include mainly *Microcoleus paludosus*, *Microcoleus vaginatus*, *Xenococcus lyngbyge*, etc.; the lichen crusts include mainly *Collema tenax*, *Psora decipiens*, *Xanthoparmelia desertorum*, *Diploschistes muscorum*, etc.; and the moss crusts dominated by mosses include mainly *Tortula desertorum*, *Crassidium chloronotos*, *Bryum argenteum*, *Tortula muralis*, etc. (Table 1). The development, succession and differentiation of the different microbiotic crusts are different between the upper, middle and lower parts of dune slopes and the interdune lowlands due to the difference of environmental conditions at the different positions of dune slopes in the Gurbantonggut Desert.

The differentiation of microbiotic crusts at the different parts of dune slopes is caused by the difference of development and converse-succession resistance of the different microbiotic crusts. For an individual dune in the Gurbantonggut Desert, the distribution pattern is different from the different species of microbiotic crusts. The animalcule community is an important component part and a vanguard species of microbiotic crusts. It exists in many species of microbiotic crusts and is extensively distributed at all the positions of dune slopes and the interdune lowlands, and it is the main species of animalcules at the top of mobile and semi-mobile dunes. These reveal that the animalcule species have a strong adaptability to the topsoil matrix of dunes. Alga crusts are distributed at the upper and middle parts of dune slopes and the interdune lowlands, in which the fully developed gray and offwhite alga crusts are distributed at the middle part of dune slopes, they are not so thick but have a certain resistance to wind erosion. The distribution height of lichen crusts is lower than that of alga crusts. Because the occurrence of lichen crusts is based on the precondition of coexistence of epiphytes and algae and the quantities of epiphytes and algae are less at the top of dunes, there are very little lichen crusts at the dune top and the upper part of dune slopes, lichen crusts are mainly distributed at the middle and lower parts of dune slopes and the interdune lowlands, they are dark gray, brown or yellow, develop in large areas, are distributed extensively, and are the main microbiotic crust species in the Gurbantonggut Desert. Moss crusts are mainly distributed at the middle and lower parts of dune slopes and the interdune lowlands, and they are black, brown or light brown, in which *Grimmia anodon* and *Grimmia pulvinata* are mainly distributed at the middle and lower parts of dune slopes, and *Bryum argenteum* and *Bryum capillare* are at the interdune lowlands. The topography of the interdune lowlands is gentle, temporary seepers of snowmelt water in spring and rainwater in summer occur easily and provide the environmental conditions for the occurrence of microbiotic crusts, especially for the sexual reproduction and growth of mosses. Therefore, microbiotic crusts are most developed at the interdune lowlands in the Gurbantonggut Desert.

Table 1. Species and distribution of microbiotic crusts in the Gurbantonggut Desert

	Species of microbiotic crusts	Distributions and characteristics
Animalcule communities	Bacilli, actinomyces and epiphytes	The top of mobile and semi-mobile dunes
Alga crusts	*Microcoleus paludosus*, *Microcoleus vaginatus*, *Xenococcus lyngbyge*, *Anabaena azotica*, *Lyngbya martensiana*, *Chroococcus turgidus* var. *solitarius*	The upper and middle parts of dune slopes Thickness: 0.18—0.25 cm in upper parts and 0.25—0.50 cm in middle parts Colour: gray and offwhite
Lichen crusts	*Collema tenax*, *Psora decipiens*, *Xanthoparmelia desertorum*, *Diploschistes muscorum*	The middle and lower parts of dune slopes and the interdune lowlands Thickness: 0.18—0.25 cm in middle parts and 0.25—0.50 cm in lower parts Colour: dark gray, brown or yellow
Moss crusts	*Tortula desertorum*, *Crassidium chloronotos*, *Bryum argenteum*, *Tortula muralis*	The lower parts of dune slopes and the interdune lowlands Thickness: 0.6—1.2 cm in lower parts and 1.5—3.5 cm in the interdune lowlands Colour: black, brown or light brown

2.2.2 Microbiotic crusts and the stability of topsoil matrix

Stability of topsoil and local climate affect the formation and development of microbiotic crusts[17]. The analyzed results of the stability of topsoil matrix where microbiotic crusts develop reveal that the stability of topsoil matrix is different from the different positions of dune slopes, and it is significantly increased from the dune top to the lower part of dune slopes, which is mainly related to the frequent occurrence and high intensity of wind erosion or aeolian sedimentation at the dune top and the upper part of dune slopes. The field investigation and wind-tunnel experiment reveal that the wind speed increases from the lower and middle parts of windward slope of dunes to the dune top, and it reaches the highest value at dune top[18,19]. The increase of wind speed speeds up the sand transport rate and the activity of sand surface at the upper part of windward slope of dunes and dune top, thus the stability of topsoil matrix is reduced. The observation on an individual dune in the Gurbantonggut Desert reveals that the transported sand quantity is increased from 1.10 g at the lower part to 5.26 g, 68.96 g and 1982.75 g at the middle and upper parts of windward slope of the dune and the dune top respectively, the transported sand quantity at the dune top is 2000 times of that at the interdune zone, the mobile sand areas are mainly distributed at the upper part of dune slopes and the dune top, and the average wind-eroded depths at the upper part of dune slopes and the dune top are 5.8 cm and 8.65—19.00 cm respectively[20]. The topsoil matrix at the lower part of dune slopes and the interdune lowlands is relatively stable. Viewing from the development and distribution of microbiotic crusts at the different positions of dune slopes, the average values of microbiotic crust thickness are 0.05—0.1 cm, 0.2—1.5 cm, 1.5—2.5 cm and 1.5—5.0 cm at the dune top, upper part, middle to lower parts of dune slopes and the interdune lowland, and their coverages are 30.5%, 48.5%, 55.5% and 75.5% respectively. These reveal that the development degree and quantity of microbiotic crusts increase from the dune top down to the lower part of dune slopes and the interdune lowlands. Furthermore, alga crusts are distributed at the upper part of dune slopes where wind erosion is serious and the stability of sand surface matrix is poor, so it can be considered that the microbiotic crusts dominated by algae have a strong converse-succession resistance and a certain adaptability to the change of dune surface matrix.

2.2.3 Change of microbiotic crusts and plant communities

The analyzed results of vegetation in the microbiotic crusts distributed regions reveal that the composition and structure of plant communities and the vegetation coverage are different from the different positions of dunes in the Gurbantonggut Desert, that is on the mobile sand surface of dune top the plant communities are dominated by *Aristida adscensionis* and accompanied by *Corispermum elongatum*, *Horaninowia ulician*, *Olgaea leucophylla*, *Agriophyllum squarrosum*, *Erysimum cheiranthoides*, etc., but the vegetation coverage is low and varies from 7.5% to 13.5%. In which the coverage of herbs needing long-term nutrients, such as *Aristida Pennata*, is below 7%, the coverage of ephemeral plants varies in a range of 1.5%—4.5%, microbiotic crusts are distributed very little, and animalcules are dominant; at the middle and upper parts of dune slopes, the plant communities include the species of *Haloxylon persicum*, *Calligonum leucocladum*, *Artemisia arenaria*, *Seriphidium terrae~albae*, etc., and the vegetation coverage varies in a range of 15.5%—28.5%. The accompanied plants are mainly *Horaninowia ulician*, *Soranthus meyeri*, *Ceratocarpus arnarius*, *Nonea Caspica*, *Chrozophora sabulosa*, *Carex physodes*, *Trigonella tenella*, *Hypecoum parvifiorum*, *Eremurus anisopteris*, *Lappula rupestris*, etc., some well-developed alga crusts are distributed here, and lichen crusts appear; at the middle and lower parts of dune slopes and the interdune lowlands, the plant communities are quite different from that at the upper part of dune slopes, they are dominated by *Ephedra distachya* and accompanied by *Geraniaceae sp.*, *Alyssum linifolium*, *Carex physodes*, *Bromus orientalis L.*, *Lappula rupestris*, etc. The vegetation coverage is high and over 35% at the lower part of dune slopes and the interdune lowlands, the species of microbiotic crusts are the most, microbiotic crusts develop mostly, in the mosses *Bryum argenteum* and *B. capillare* are distributed near the short shrubbery of *Ephedra distachya* at the interdune lowlands, and the plants grow densely in plots. However, the correlation between the change of plant community structure and the formation and development of microbiotic crusts at the different positions of dune slopes is not understood yet, and the effects of mosses and lichens distributed extensively at the interdune lowlands on the development and succession of the communities of *Ephedra distachya* in the formation of microbiotic crusts are needed to be further researched.

3 Conclusions and discussion

The following conclusions may be drawn from our study:

(1) The microbiotic crusts in deserts cannot only fix sand surface of dunes, but also have the ecological functions in changing the physiochemical properties of soils in deserts and affecting the surface hydrological process and soil nutrient circulation. In the Gurbantonggut Desert, the soil organic matter content increases obviously from the middle part of dune slopes to their lower part and the interdune lowlands, which is related to the environmental conditions and the activity of animalcules in the formation of microbiotic crusts. Humus soil forms continuously on dune surface under the effects of mosses and lichens, which promotes effectively the accumulation of organic matter in poor soil and the increase of soil nutrients.

(2) The formation and development of microbiotic crusts are strongly affected by the change of the stability of topsoil matrix, local climate and soil physiochemical properties. For an individual sand dune, the development degree, quantity and thickness of microbiotic crusts increase from the upper part of dune slopes to their middle and lower parts and the interdune lowlands. The development and differentiation of microbiotic crusts at the different parts of dune slopes are the ecological appearance and natural selection of synthetic adaptability of the different microbiotic crust species to the local environmental conditions, and are closely related to the ecological conditions. It is considered that the converse-succession resistance of alga crusts is stronger than that of moss crusts and lichen crusts based on the analyzed results of the distribution and development of these three species of microbiotic crusts at the different morphological positions.

(3) The species composition and succession of microbiotic crusts at the different developing stages are closely related to the soil and vegetation change. During the formation process of soil microbiotic crusts, algae begin to grow around the roots of psammophytes and form alga-root crusts at first. Subsequently, lichens begin to grow. Lichens have an azofication, and mosses begin to grow after algae and lichens improve soil structure and soil moisture capacity[21]. Humus soil forms continuously on dune surface under the effects of mosses and lichens, which promotes effectively the accumulation of organic matter in poor soil and the increase of soil nutrients. The development and succession of microbiotic crusts play an important role in improving soil structure, which

not only redounds to the stabilization of dune surface and the formation of fixed dunes, but also provides the conditions for the growth of herbs and woody plants[22,23]. In the Gurbantonggut Desert, the lower part of dune slopes and the interdune lowlands are the areas where microbiotic crusts develop best, plants grow relatively well, and ephemeral and ephemeral-like plants grow densely, their correlations, however, need to be further researched.

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