Biological soil crust formation under artificial vegetation effect and its properties in the Mugetan sandy land, northeastern Qinghai-Tibet Plateau

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Abstract. Mugetan sandy land is an inland desertification area of about 2,065 km² in the northeastern Qinghai-Tibet Plateau. In the ecological restoration region of the Mugetan sandy land, different crusts have formed under the action of vegetation in three types of sandy soil (i.e. semi-fixed sand dune, fixed sand dune and ancient fixed aeolian sandy soil). The surface sand particle distribution, mineral component and vegetation composition of moving sand dunes and three types of sandy soil were studied in 2010-2014 to analyze the biological crust formation properties in the Mugetan sandy land and the effects of artificial vegetation. Results from this study revealed that artificial vegetation increases the clay content and encourages the development of biological crust. The fine particles (i.e. clay and humus) of the surface layer of the sand dunes increased more than 15% ten years after the artificial vegetation planting, and further increased up to 20% after one hundred years. The interaction of clay, humus, and other fine particles formed the soil aggregate structure. Meanwhile, under the vegetation effect from the microbes, algae, and moss, the sand particles stuck together and a biological crust formed. The interconnection of the partial crusts caused the sand dunes to gradually be fixed as a whole. Maintaining the integrity of the biological crust plays a vital role in fixing the sand under the crust. The precipitation and temperature conditions in the Mugetan sandy land could satisfy the demand of biological crust formation and development. If rational vegetation measures are adopted in the region with moving sand dunes, the lichen-moss-algae biological crust will form after ten years, but it still takes more time for the sand dunes to reach the nutrient enrichment state. If the biological crust is partly broken due to human activities, reasonable closure and restoration measures can shorten the restoration time of the biological crust.

1. Introduction

Extensive arid area including desert, Gobi, and sandy land exists in the western China, where vegetation is scarce. However, sparse vegetation plays a crucial role on ecological environment on the edge of deserts [16,17,39,45]. Vegetation exerts good ecological functions of windbreak and sand fixation, moreover, it boosts formation of biological crust [4,9,40]. Biologic crust is the organic complex formed by interaction of soil particles, organic matter and its metabolites and microbes, algae, lichens, and mosses [1,23], which serves a significant ecological and environmental function in the...
Biological crust may partly change the local land desertification by transforming sand to soil to improve the ecological environment and land use [20]. Moss, as the dominant species in the biological crust, marks the maturity of the crust [19]. The development of the moss crust reaches the optimum when the sand dune has a strong capacity of water storage and fixed sand and the greatest resistance to mechanics disturbance [2,43,32]. Consequently, it is extremely important to repair damaged biological crust and accelerate the formation of biological crust in desertification control areas (e.g. in western China).

Biological crust develops slowly. Once the biological crust is damaged by human activities (e.g. fire and grazing), it takes a long time to fully restore. The recovery speed of biological crust depends on the crust type, disturbance intensity and frequency. Moreover, algae crust recovers faster than lichen and moss crusts [32]. In general, the full elementary recovery of the crust takes at least 1-5 years; the restoration to a thicker crust takes about 50 years; and the restoration of moss and lichen crusts takes about 250 years [37,29,14]. However, if the disturbance is effectively controlled, reasonable vegetation measures can result in the recovery of the biological crust in a relatively short time [46,30].

Mugetan sandy land is one of the most seriously desertified areas in the Gonghe Basin of the northeastern Qinghai-Tibet Plateau [3,27]. The Huangshatou zone is on the edge of the Mugetan sandy land, and has the strongest interaction between vegetation growth and sand storm activity. Since the late 1980s, the local government has implemented a series of control and restoration projects to fix moving sand dunes in the Huangshatou zone. Currently, moving sand dunes in the Huangshatou zone have been fixed with more than 30% coverage of shrubs and herbs, and even more than 60% of shrub-herb-moss structures in some areas. Moreover, biological crust has developed and reached a stable ecological sand-fixation state [49,18]. It is evident that the ancient sand dunes, most of which are several hundred years old [7], have lost their dune shape and covered by vegetation with 90% coverage. It is important to explore the formation and role of biological crust on the restoration process especially since the process of biological crust development in the Mugetan sandy land has not been documented. More importantly, the successful management experience of ecological restoration in the Huangshatou zone of the Mugetan sandy land is worth referencing and promoting. The objective of this study is to analyze the process and characteristics of biological crust in vegetation restoration zones base on the control practice and vegetation effect in the Mugetan sandy zone, the acceleration effect of artificial vegetation on biological crust, and the restoration time of the damaged biological crust.

2. Study area and methods

2.1. Study area
The Mugetan sandy land is a desertification area of about 2,065 km² near Yellow River source. It is located at 100°24 '~ 101°22' E, 35°27 '~ 35°47' N at an altitude of 3000~3400m, near east of LongyangxiaReservoir. It is a typical inland desert bottomland. The annual mean temperature in this area is 2.4°C; the annual mean precipitation is about 400mm, and the annual mean evaporation is about 1,500mm. Dominant wind direction is south and southeast with an annual mean wind speed of 3m/s and the maximum annual mean wind speed of 14 m/s. The annual gale (wind speed equal to or higher than 7m/s) blows for 12 days. Overall, this region has the characteristics of alpine, arid, and windy climate.
Figure 1. Location of the Mugetan sandy land near Yellow River source and four sampling points.

Figure 2 shows the topography and landscape of the Mugetan sandy land. Early lake sediments with the plateau uplift are exposed on the ground. The fine sand provides rich material sources for the aeolian sand [48]. The Mugetan sandy land is a transitional type between the northwest extremely arid desert zone and the semi-arid loess plateau zone. The desertification takes place in a periodic or non-periodic alternative process and indifferent degrees, and the desertification and its inverse processes exist side by side [47].

Figure 2. Topography and landscape of the Mugetan sandy land.

Since 1970s, in order to reduce aeolian sand disaster, a series of control measures have been implemented, e.g. closing hillsides, afforestation, planting grass to fix sand dune and restore grassland, and forbidding overgrazing, deforestation, and unreasonable land use. Subsequently, vegetation started growing, the desertification area started reducing, and grassland was restored to some extent. In addition, on the front edge of the Mugetan sandy land, i.e. the Huangshatou zone, vegetation restoration projects were implemented, such as afforestation and laying checkerboard barriers to fix moving sand dunes. Along with the reinforced sand control engineering and artificial vegetation influence, a belt of a few kilometres long with semi-fixed and fixed sand dunes appeared in the front edge of the Huangshatou zone as shown in figure 2.
The desertification area of Mugetan sandy area was about 2,065 km$^2$ in 2005. Compared to the measurements in 1990, the area of desertification had been gradually reducing, especially during 2000 to 2005, when the moving sand dune reduced by 41.76 km$^2$ [3]. Obviously, implementing effective control measures and vegetation restoration can inhibit desertification expansion and encourage grassland recovery.

Figure 3. Afforestation zone of Huangshatou in the Mugetan sandy land (a) semi-fixed sand dune with 20-30% vegetation coverage; and (b) fixed sand dune with 50-70% vegetation coverage.

2.2. Study method
In this study, the ecological restoration condition of the Mugetan sandy land is divided into four types: moving dune, semi-fixed dune, fixed sand dune, and ancient fixed aeolian sand soil. For each of these four representative types of sandy soil, the biological crust, fine sand beneath the crust, and vegetation composition were sampled and analyzed. In July and August of 2010-2014, field investigations were conducted in the vegetation restoration area of the Huangshatou, including sand sampling and vegetation measurement (A1, SF2, and F5), and a site of ancient fixed aeolian sand soil (F1) (shown in figure 1).

The meteorological data (i.e. rainfall, temperature, wind) in 1961-2011 were obtained from the meteorological station of Guinan County and relevant literatures [11,12,41]. Soil sampler drilling was used to obtain sand samples from typical dune surface and deep layer, with each sample weighing about 300 g. Sediment coarser than 0.075 mm was analyzed using the sieving method. For sediment finer than 0.075 mm, the LA-920 laser particle size analyzer was used to analyze the particle size gradation so as to obtain the particle size distribution. The total rock mineral and clay mineral composition of sandy soil samples were quantitatively analyzed by an X-ray diffraction instrument with 0.01% accuracy. The organic matter content was determined using the potassium dichromate oxidation plus heating method, with a detection standard of NY/T 1121.6-2006 and error less than 1 g/kg. The sodium pyrophosphate extraction-potassium dichromate oxidation method was used to determine the humus content, with a testing standard of LY/T 1238-1999 and error less than 1 g/kg.

For repeated sampling of the sand dunes within each time period, herbs of 1×1 m$^2$ quadrat were taken (five repeats) and the shrubs of of 5×5 m$^2$ quadrats were taken (two repeats). The number of vegetation species, number of trees, height, and coverage, and the species of the samples collected were identified. The vegetation coverage, richness (i.e. the number of species), and average height of the vegetation on the windward and leeward sides of the dunes in each sample were statistically analyzed. Based on the species composition of multiple samples and the numbers of the species, the importance parameter of each species were calculated, namely the total value of the relative density, relative coverage, and relative frequency of each species. The relative density, relative coverage, and
relative frequency are the percentages of the density, coverage, and frequency of each species to the total density, coverage, and frequency of all species [8]. The summation of the important parameters of the same species is an important value of the vegetation components.

3. Results

3.1. Meteorological factor

Figure 4 (a) shows the average annual temperature recorded at the Guinan meteorological station from 1961 through 2010. Since 1961, the temperature has shown a rising trend with an annual average temperature of 2.4°C. The annual temperature from 1998 through 2010 was higher than the multi-year mean temperature from 1961 through 2010. Obviously, the rising temperature was conducive to afforestation, forest and vegetation development. Figure 4 (b) and (c) show the annual average precipitation and evaporation amount recorded at the Guinan meteorological station from 1961 through 2010. The average annual rainfall was about 400mm, and the annual average evaporation was 1500mm. The annual evaporation was much higher than the annual rainfall. The annual rainfall from 2000 through 2010 was higher than the multi-year mean rainfall from 1961 through 2010, whereas, the annual evaporation from 2000 through 2010 was lower than the multi-year mean evaporation from 1961 through 2010. Since 2000, the precipitation condition has been conducive to the development of vegetation. Figure 4 (d) shows the annual maximum wind speed recorded at the Guinan meteorological station from 1961 through 2010. The graph shows a downward trend since 1961. From 1991 through 2010, the annual maximum wind speed became lower than the annual multi-year maximum wind speed from 1961 through 2010. In 2003, the maximum wind speed reduced to 10m/s. Decreasing wind speed reduces the wind-blown sand, which is advantageous to dune fixation. Therefore, in the past 20 years, the meteorological conditions have been in favor of desert vegetation restoration in the Mugetan sandy land.
3.2. Feature of sand dune

Figure 5(a) shows a moving sand dune (A1) with a crescent shape, a height of 7-10m, less than 5% surface vegetation cover, and the sand in the flow state. Figure 5(b) shows that a semi-fixed dune (SF2) which has vegetation coverage of 5-20%. A large area of the physical crust is covered locally with weak algae crust after 14-15 years of artificial planting. However, these crusts are too fragile to effectively inhibit sand movement. If the crust is breached, sand below the crust will be activated again. Additionally, even though the semi-fixed sand dune is relatively flat, it still maintains a certain dune shape. Figure 5(c) shows fixed sand dune with 40% vegetation coverage and a large area of moss crust with 3-5 cm thickness after 30 years of artificial planting. Ancient fixed aeolian sandy soil is widely distributed in the Mugetan sandy land. One example (F1) is shown in Figure 5(d). After experiencing vegetation effect for hundreds of years, the ancient fixed aeolian sand soil has more than 60% vegetation coverage and a thick humus layer (15-18 cm) including a surface biological crust (4-5 cm). The height of the ancient fixed aeolian sandy soil is less than 0.5m and the area is almost flat.

Figure 4. Change of four climate factors from 1961-2010 in the Mugetan sandy land.
3.3. Variation of particle composition

Figure 6 shows the grain distribution curves of the surface of sand dunes in different stages, and Table 1 demonstrates the particle composition characteristics of the surface of the sand dunes under the artificial vegetation effect. The composition of the moving sand dune is uniform with the median size $d_{50}=0.15\text{mm}$ and the sorting coefficient $\sigma=1.2$. In particular, the grain distribution curve displays a steep slope between 0.2~0.1mm, and 95% of the particles have particle sizes of 0.1~0.2mm. After the implementation of vegetation restoration measures, under the effect of rainfall and vegetation, the surface particles of moving dunes became weathered, which resulted in a substantial amount of fine particles (less than 0.05mm) including fine sand, silt, and clay. At the semi-fixed sand dune stage, $d_{50}=0.13\text{mm}$, and $\sigma=1.3$. The 0.1-0.2mm particles counted for 80% of the total particles, and the fine
particle content became 5%. At the fixed sand dune stage, \(d_{50}=0.11\) mm, and \(\sigma=1.4\). The 0.1-0.2 mm particles counted for 70% of the total particles, and the fine particle content increased to 15%. The surface particle content of the ancient fixed aeolian sand soil indicates that after nearly one hundred years of vegetation restoration, fine particles significantly increased to 23.5%, the 0.1-0.2 mm particles dropped down to 50%, with \(d_{50}=0.09\) mm, and \(\sigma=2.6\). Consequently, after experiencing vegetation restoration for several years, the proportion of fine particles greatly increased, and the fine particle content increased to over 15% after several decades, and more than 20% after one hundred years.

Figure 6. Grain size distribution of biological crust samples of four sandy soils.

Table 1 shows the comparison of particle sizes at the surface and deep layers. According to Table 1, weathering was not obvious in the moving sand dune, i.e. no difference in the particle composition between the surface and deep layers. Weathering had occurred in the semi-fixed sand dune with locally forming crust and the fine particle content in the crust layer being 3-4% higher than that in the deep layer. For the fixed sand dune, due to long-term weathering and soil formation, the humus layer had formed and the fine particle content in the humus layer was 10% higher than that in the deep layer. For the ancient fixed aeolian sand soil, the fine particles inside the thick humus layer were 20% higher than that in the deep layer.

Table 1. Particle characteristics of four sandy soils under artificial vegetation restoration.

| No. | Thickness of biological crust (cm) | Depth (cm) | Sorting coefficient \(\sigma\) | Median size (mm) | Fine particle content (%) | Grain size content (%) |
|-----|----------------------------------|-----------|-------------------------------|-----------------|--------------------------|------------------------|
|     |                                  |           |                               |                 |                          |                        |
|     |                                  |           |                               |                 |                          | 0.25–0.1 (mm)          |
|     |                                  |           |                               |                 |                          | 0.1–0.05 (mm)          |
|     |                                  |           |                               |                 |                          | <0.05 (mm)             |
| A1  | 0                                | 0         | 1.273                         | 0.15            | 1.017                    | 95.0                   |
|     |                                  | 10        | 1.225                         | 0.13            | 1.244                    | 95.4                   |
|     |                                  |           |                               |                 |                          | 5.0                    |
|     |                                  |           |                               |                 |                          | 1.3                    |
| SF2 | 1                                | 0         | 1.316                         | 0.13            | 5.019                    | 80.0                   |
|     |                                  |           |                               |                 |                          | 15.0                   |
|     |                                  |           |                               |                 |                          | 5.0                    |
|     |                                  | 10        | 1.219                         | 0.16            | 1.200                    | 96.6                   |
|     |                                  |           |                               |                 |                          | 1.4                    |
|     |                                  |           |                               |                 |                          | 2.0                    |
| F5  | 2-4                              | 0         | 1.449                         | 0.11            | 15.730                   | 70.0                   |
|     |                                  |           |                               |                 |                          | 18.0                   |
|     |                                  |           |                               |                 |                          | 12.0                   |
|     |                                  | 20        | 1.262                         | 0.14            | 0.851                    | 91.7                   |
|     |                                  |           |                               |                 |                          | 5.6                    |
|     |                                  |           |                               |                 |                          | 2.7                    |
3.4. Characteristics of mineral particle change

Figure 7 shows the mineral composition and content of the sand dunes at the four stages. The contents of the measured minerals were mainly quartz, feldspar, carbonatite, amphibole, and clay minerals which refer to layered silicate minerals (particle size less than 0.002mm), such as kaolinite, illite, smectite, chlorite, illite and smectite mixed layer, and green smectite interstratified minerals.

The content of clay minerals in the moving sand dune was about 9%, and the content of non-clay minerals was 91%. The content of clay minerals in the surface layer of the semi-fixed sand dune was 13.8%, while the content of the non-clay minerals was 86.2%. The content of clay minerals in the crust of the fixed sand dune was 16.2%, while the content of non-clay minerals was 83.8%. The content of clay minerals in the crust of the ancient fixed aeolian sand crust was 23.7%, while the content of non-clay minerals was 76.3%. These results show that the content of clay minerals increased to nearly twice as much after the sand dunewas fixed, and the clay content in the ancient fixed aeolian sand crust was two times more than that in the moving sand dune after the long-term effect of vegetation. Moving sand dunes became fixed aeolian sandy soil after several decades with the clay minerals increasing greatly. During the following decades, the thickness of humus crust increased, and the clay particles inside the crust increased with time.

The humus content in the moving sand dune was 4.2g/kg, and that in the ancient fixed aeolian sand was 16.67g/kg. Under the effect of vegetation, the increase of the clay mineral and humus content is the primary factor in the process of moving sand dune becoming fixed aeolian sand.

|    | (humus layer of 15-18 cm) | 0  | 2.613 | 0.09 | 23.460 | 50.0 | 25.0 | 25.0 |
|----|--------------------------|----|-------|------|--------|------|------|------|
| F1 | 50                       | 1.348 | 0.14 | 2.429 | 91.8 | 5.4 | 2.8 |

Figure 7. Mineral particle contents of four sandy soils.

3.5. Effect of vegetation on biological crust

The vegetation was planted in the Huangshatou ecological restoration area of the Mugetan sandy landas Cathay poplar (*Populus cathayana*) since the late 1990s. Table 3 shows the composition of the herbaceous vegetation in the sand dunes in three stages under the planting vegetation effect including moving sand dune (A1), semi-fixed sand dune (SF2) and fixed sand dune (F5). The vegetation succession process and effect of vegetation on biological crust were analysed. And also the ancient fixed aeolian sandy soil (F1) of hundred years old was comparatively analysed.

During the stage of moving sand dune, the restoration measure was to plant poplar seedlings with tree diameters of 1-2cm at spacing of 2-3 m, and ground scattered sedge family (e.g. *Carex moorcroftii*) and gramineous family (e.g. *Bromus tectorum*).

During the semi-fixed sand dune stage, the artificial vegetation fixed the sand dune after 15 years [45], and herbaceous vegetation developed with invasion of microbes, algae, lichens in the surface particles layer. Meanwhile, under the climatic factors and vegetation effect, the surface particle composition and soil structure of the sand dune changed, i.e. hydrolysis or carbonation occurred to the...
feldspar and carbonate minerals and illite, kaolinite, chlorite, and illitesmectite mixed-layer clay minerals were generated. This process resulted in particles fining and gradual accumulation with time. Aggregation of plant residues and animal carcasses and faeces in the sand dune surface provided large amounts of organic matter that yielded the humus under the action of microorganisms. After 15 years of vegetation development and succession, the vegetation coverage reached 30%, and the herb layer was composed of 2 families and 2 species, i.e. dominantly Carex moorcroftii and Oxytropis falcata Bunge. At this time, the humus, clay particles, microorganism, and algae vegetation united with each other in localized areas of the semi-fixed sand dune and complex organic compound formed. This primary biological crust played an important role for fixing the sand dune. The biological crust influences vegetation succession and turns the early shrub-dominated system into an herbaceous vegetation system.

During the stage of fixed sand dune, the fine sand, silt, and clay increased greatly, with the invasion of microbe, algae, lichens, and mosses, and bacteria and fungi growth. Meanwhile, vegetation interception and atmospheric dustfall (mainly clay) resulted in sediment deposition [6]. These effects promoted sand particles sticking and the formation of soil aggregate structure and stable organic complex, and finally a biological crust with a certain thickness developed. After the vegetation had experienced development and succession for more than 30 years, the vegetation coverage reached to more than 60% with the height of Populus cathayana reaching 3m and the tree trunk diameters reaching 8-12cm. The herb species composition included 8 families and 10 species, dominantly Oxytropis falcata Bunge and Carex moorcroftii, and accompanied by Artemisia annua L. and Kalidium foliatum Moq. After the sand fixing by planting wood Missy Populus cathayanaaand vegetation restoration for ten years, plant communities with Carex moorcroftii as the dominant species gradually developed in Oxytropis Falcata Bunge in the ecological recovery area. Interaction between the vegetation and sand particles with lichens and bryophytes encroachment accelerated the rate of mineral weathering and accumulated the clay and other particles for soil formation. In the ecological restoration area in the Mugetan sandy land, the fine particle content increased more than 15% after several decades and increased up to 20% after one hundred years.

In the ancient fixed aeolian sandy soil, due to vegetation development and succession after decades and even hundreds of years, the vegetation coverage reached 95% with 10 species in 6 families, mainly including local perennial Poa Tibetica, Elymus dahuic, and Carex moorcroftii. These vegetation species in the Mugetan ecological restoration area are dominant species of the plant community. They have dense root, resistance to drought and sand burying, and play an Important role on fixing sand dunes. Meanwhile, the biological crust changed the physical and biological properties of the subjacent sand, and transform sand to soil. To present, there formed a thick humus layer and the thickness has increased up to tens of centimetres, containing a large number of plant roots.

Compared to the ancient fixed aeolian sandy soil, after 30 years of the artificial planting, the vegetation coverage has gradually increased to 45% (11 species), and the effect of herbaceous vegetation on sand fixation has been enhanced. The number of vegetation species in the artificial vegetation zone was the same as that in the ancient fixed aeolian sandy soil. It indicates that the artificial vegetation accelerates the vegetation succession process, which is consistent with conclusions by previous researchers[15,42]. In addition, after 15 years of artificial planting, the fine particles has increased by 15% and the clay mineral particles have reached 16%, equivalent to 67% and 68%, respectively, of that in the ancient fixed aeolian sandy soil. It indicates that artificial vegetation promotes the increase of the clay content and the development of the biological crust, but the clay and nutrient still need more time to reach the enrichment state.

Table 2. Herb characteristics of four sandy soils.

| No. | Elevation (m) | Height of dune (m) | Slope type | Coverage (%) | Richness | Species composition / Important value |
|-----|---------------|-------------------|------------|--------------|----------|--------------------------------------|
| A1  | 3363          | 9                 | Windward slope | 2.5          | 1        | -                                    |
|     | Leeward slope | Windward slope | Windward and Leeward slope | Windward and Leeward slope |
|-----|---------------|----------------|---------------------------|---------------------------|
| SF2 | 3369          | 3              | 3                         | 1                         |
|     | 4             | Leeward slope  | Carexmoorcroftii          | Carexmoorcroftii          |
|     |               | 30             |                           |                           |
|     |               |                 |                           |                           |
|     |               |                 |                           |                           |
| F5  | 3356          | 45             | 1                         | 11                        |
|     |               |                 |                            |                           |
|     |               |                 |                           |                           |
|     |               |                 |                           |                           |
| F1  | 3184          | 95             | 0.5                       | 11                        |
|     |               |                 |                           |                           |
|     |               |                 |                           |                           |

4. Discussion
Many deserts and sandy lands in western China have developed localized mature biological crust under the influence of artificial and natural vegetation. Previous studies by researchers have investigated biological crusts in many deserts and sandy lands in western China. Table 3 shows the characteristics of biological crust on sand dune surfaces under diverse vegetation effects in western China. Owing to the complexity of influencing biological crust growth, the thickness and development degree of the biological crusts in different sampling locations are totally different, even at the same time and in the same area. For example, the Horqin sandy land in Inner Mongolia and the Mu Us sandy land in Yulin have better water and heat conditions (400 mm/yr rainfall and 6-8°C annual mean temperature) than many other sandy lands. Twenty-five years after vegetation planting and aerial seeding in the Horqin sandy land, a moss crust has developed with a thickness of 15 mm and a fine particle content of 15% [13,46]. Thirty-one years after artificial vegetation planting in the Mu Us sandy land, a moss crust has developed with a thickness of 10.3 mm and a fine particle content of 12.6% [33]. In contrast, in the Shapotou area of the Tengger Desert, the water and heat conditions are poor, with the annual mean rainfall of 180 mm the evaporation of 3,000 mm, and the annual mean temperature is 9.7 °C. The biological crust only developed to a thickness of up to 11 mm and a fine particle content of 24.42%
[19,37]. The Gurbantunggut sandy land in Xinjiang Province also has low rainfall (150 mm) and high evaporation (2000 mm), the natural moss crust only developed to a thickness of 45 mm and a fine particle content of up to 25% [22].

The Mugetan sandy land is located in the plateau region at an elevation of 3000 m, and has a low annual mean temperature of 2.4 ºC with the annual mean rainfall of 400 mm and the evaporation of 1,500 mm. After 30 years of vegetation restoration in the desertification control area, a mature moss crust has developed on the sand dune surface with a thickness of 20-40 mm and a fine particle content of 12%. Therefore, the Mugetan sandy land naturally has suitable water and heat conditions. Moisture and temperature play a crucial role on biological crust development because good hydrothermal conditions benefit the invasion and growth of microbial and plant, accelerate the micro-environment process, and encourage the formation of soil aggregate structure and biological crusts. As long as reasonable vegetation measures are adopted, biological crust can develop in a relatively short time. For the ancient aeolian sandy soil, a natural humus layer with a thickness of 10-20 mm formed under the action of biological crust, which has a thickness of 4-5 mm and a fine particle content of 25%. It can be seen that mature biological crust can be developed as long as external disturbance is reduced or controlled, and change the subjacent sand to soil with humus layer.

The effect of vegetation exerts a significant role on crust formation. Vegetation restoration promotes composition change of the dune surface particles from loose particles to soil aggregate structure with biological crust. The crust layer fixes dunes and promotes ecological restoration, which is consistent with previous research see [13]. The vegetation measures to fix sand are to plant shrubs and trees, e.g. planting Populus in the Mugetan sandy land. The shrub intercepts atmospheric dustfall, and its own litter has important effect on the formation of biological crust. Silt, clay, organic matter, and humus significantly increase under the shrub canopy which reduces wind speed and improve the water and heat conditions and micro-environment in the ground, promoting the formation of biological crust [5, 21, 28, 24]. Then the crusts under the canopy cause the surface sand and the surrounding sand to be gradually fixed. Finally, the interconnection of these crusts makes the sand dunes be fixed as an integral body [10, 35]. Therefore, the sand fixing process is accelerated by implementing artificial vegetation measures, and the shrub-herb-biological crust community forms in a short time and good results of ecological restoration can be achieved.

Table 3. Biological crust characteristics of sand dunes under vegetation effect in different deserts and sandy lands of western China.

| Desert area                  | Elevation (m) | Mean annual precipitation (mm) | Average Annual temp. /°C | Wind speed (m/s) | Enclosing time (year) | Sand-fixing measures                  | Crust type | Thickness (cm) | Fine particle content (%) |
|------------------------------|---------------|--------------------------------|--------------------------|-----------------|-----------------------|---------------------------------------|------------|-----------------|--------------------------|
| Horqin Sandy Land, Inner Mongolia | 360           | 366|1935                      | 6.4|3.2-4.1           | 15                     | Artificial planting (Populus)           | Moss       | 1.2             | 22                       |
| Mu Us sandyland, Yuling, Shanns | 1100          | 415|2500                      | 7.9|2.1-3.3           | 31                     | Artificial planting, seeding           | Moss, algae | 1.03            | 12.58                    |
A large area of biological crust can greatly improve the resistance to aeolian erosion. Wind tunnel tests have shown that under 25-30 m/s wind speed, sand dunes with biological crusts have no erosion. Therefore, maintaining the integrity of the biological crust is extremely important in improving the resistance of aeolian erosion [36]. Biological crusts can well adapt to harsh environment. The biggest threat is grazing, firing, and mechanical disturbance [38]. Disturbance from grazing, firing, and mechanical not only affects the physical structure and chemical properties of soil, but also leads to fragmentation of the biological crust structure [25]. Once the biological crust is damaged, especially if the damage area exceeds the critical damage rate [31], even low wind speed can cause severe aeolian erosion on bare sand surfaces. According to the results from previous studies [31], the annual maximum wind speed is up to 14 m/s in the Mugetan sandy land, and the critical damage rate for the moss crust and the alga crust are 30% and 10%, respectively. At present, moss-algae interactive biological crusts can control aeolian erosion in the Huangshatou restoration area under the measures of afforestation, straw checkerboard barriers, and vegetation fencing.

5. Conclusions
These studies reveal that the water and heat conditions satisfy the demand of the biological crust development, and artificial vegetation increases the clay content and promotes the development of biological crust in the Mugetan sandy land. The fine particle content of the sand dune in the Mugetan sandy land has increased by 15% in a short time scale (decades) and up to 20% in a long time scale (one hundred years). The content of clay minerals increased to nearly twice more than that in the movable sand dune. The clay and humus have formed the soil aggregate structure, promotes a stable formation of the biological crust and greatly enhances soil formation and the resistance to aeolian erosion. The lichen-moss-algae biologic crust will appear under reasonable measures after 30 years in moving sand dune regions in the Mugetan sandy land. If the biological crust suffers disturbance from human activities or extreme weather, reasonable closure and repairing measures can shorten the recovery time.
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