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# The Soil and Water Conservation Effects of Different Plant Communities and Biological Soil Crust Symbiosis Patterns in the Ecologically Fragile Area of Central Ningxia

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**Abstract:** Biological soil crusts are complex biological soil layers formed by mosses, lichens, cyanobacteria, and the underlying soil, which together with plants affect rainfall infiltration, surface runoff, soil evaporation, and water movement in the soil. The soil desertification and soil erosion in the ecologically fragile areas of central Ningxia are serious problems, and the ecological environment is extremely fragile. Effective ecological restoration technologies are urgently needed. This study took the grassland in the ecologically fragile area of central Ningxia as the object and investigated the impact of three plant communities and symbiotic patterns of biological soil crusts on soil erosion through field simulated rainfall experiments. The results showed that: (1) At a rainfall intensity of 90 mm $h^{-1}$, the initial runoff time of each slope was significantly positively correlated with plant community type and biological soil crust coverage, and prolonged with the increase of plant community type and biological soil crust coverage. (2) With the extension of rainfall duration, the cumulative runoff on each slope exhibited an increasing trend. (3) The sediment concentration in runoff on slopes under different plant community and biological soil crust symbiotic patterns was significantly different, with the sediment concentration decreasing as the type of plant community and the coverage of biological soil crusts increased. (4) With the increase in the diversity of plant communities and the coverage of biological crusts, there was a gradual reduction in the volume of accumulated sediment. This study offers scientific management strategies and practical guidance for soil and water conservation efforts in the ecologically vulnerable areas of central Ningxia, highlighting the importance of promoting these symbiotic models within the region.

**Keywords:** biological crust; plant community; simulated rainfall; soil erosion; soil and water conservation effect; ecologically fragile area

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## 1. Introduction

The effect of soil and water conservation refers to a series of positive impacts achieved through a range of measures and management strategies to reduce or prevent soil erosion and land degradation, thereby protecting land resources and maintaining or enhancing land productivity [1]. Soil erosion refers to the phenomenon of soil erosion and land degradation caused by natural factors such as wind and water or human activities [2]. It not only leads to a decline in soil fertility but can also cause a series of environmental issues, including river sedimentation, water pollution, and ecological destruction [3]. Previous studies on the effects of soil and water conservation under plant communities and biological crust cover have mainly focused on single factors. However, under natural conditions, biological crusts are often distributed in the gaps between plants or under the canopy, co-covering the ground surface with plants and working together to prevent soil erosion, reduce the kinetic energy of rainfall, and resist raindrop impact [4]. According to relevant studies, slopes covered by both plants and biological crusts still exhibit significant benefits in reducing runoff and sediment [5,6]. Biological crusts are complex biological soil

layers formed by mosses, lichens, cyanobacteria, and the underlying soil, which can be divided into three categories: algal crust, lichen crust, and moss crust [7,8]. They play a significant role in resisting water erosion. The growth of biological soil crusts increases the roughness of the soil surface, which helps to slow down the flow of water and reduce the scouring force on soil particles [9]. Microorganisms and plant roots within the biological soil crusts can secrete sticky substances, such as polysaccharides, which aid in binding soil particles together, forming stable soil aggregates, thereby enhancing the stability of the soil structure. Organisms within the biological soil crusts can absorb and store water, which helps to reduce surface runoff and lower the likelihood of water erosion. Plant bodies in the biological soil crusts, particularly lichens and mosses, can form a physical barrier that directly blocks the direct impact of raindrops on the soil surface [10]. The biological activity of the biological soil crusts promotes the accumulation of organic matter, which increases the aggregation and stability of the soil, thereby enhancing its resistance to erosion. Biological soil crusts cover the soil surface, reducing the area of exposed soil and thus decreasing the chances of water erosion [11]. In addition, biological crusts are also considered an effective means of ecological restoration [12], used in soil and water conservation projects such as the "Three-North" project [13], effectively preventing the spread of desertification through adaptive measures [14,15].

Biological soil crusts and plants engage in a complex symbiotic relationship that is pivotal for sustaining ecological equilibrium, enhancing soil quality, facilitating plant proliferation, and mitigating soil erosion. In arid zones, water availability is a critical constraint on plant growth and ecosystem functionality. Biological soil crust reduces evaporation and increases water infiltration and retention through its physical structure [16]. The synergistic interaction between microbial communities within the crusts and plant roots establishes a micro-scale hydrological cycle that sustains soil moisture in arid conditions, ensuring adequate hydration for plants [17]. Microbes in biological soil crusts engage in nitrogen fixation, converting atmospheric nitrogen into a form accessible to plants, and decompose organic matter, releasing essential nutrients such as phosphorus and potassium. These processes enhance soil fertility and provide abundant nutrients for plant uptake. Moreover, biological soil crusts contribute to the accumulation of soil organic matter, further ameliorating soil structure and fertility [18]. The presence of biological soil crusts markedly improves soil stability, diminishing the impact of wind and water erosion. The biological components of biological soil crusts, via their growth and metabolic activities, bind soil particles into aggregates, forming a protective layer that effectively prevents soil particle loss [19]. This is particularly vital in arid and semi-arid regions, which are frequently threatened by windblown sand and soil erosion. Biological soil crusts also offer a relatively stable microenvironment conducive to plant root development and nutrient absorption. In return, plant growth provides essential organic matter and habitat for microbial life within the crusts, fostering a mutually beneficial symbiosis [20–22]. This symbiotic model supports plant growth and propagation, thereby enhancing biodiversity and ecosystem stability. Microbes and plants within biological soil crusts sequester atmospheric carbon dioxide through photosynthesis, aiding in the mitigation of global climate change [23,24]. Biological soil crusts are resilient to extreme environmental conditions, such as drought and salinity, offering a stable microenvironment for plants and fostering ecosystem adaptability and resilience [25]. In essence, the symbiotic relationship between biological soil crusts and plants is multifaceted and critically important in the ecosystems of arid and semi-arid regions, with profound implications for ecological restoration and sustainable management [26]. By comprehending and preserving this symbiotic relationship, we can more effectively maintain ecological balance in arid regions and promote the health and sustainable development of ecosystems [27]. The symbiotic relationship between different plant communities and biocrusts is an important area of research in arid and semi-arid ecosystems. In the symbiotic mode of desert plant communities and biocrusts, the root systems of these plants help to fix the soil and reduce wind and water erosion, while their remnants provide a source of organic matter for the formation of biocrusts. The presence of

biocrusts further protects the soil from erosion, improves soil structure and fertility, and provides a good microenvironment for the sustainable growth of plant communities. The symbiotic relationships between different plant communities and biocrusts are complex and diverse, and they work together for soil health and ecological balance in arid and semi-arid regions [28]. By studying these symbiotic relationships, we can better understand the function and stability of ecosystems, and provide a scientific basis for ecological restoration and management in arid areas.

Scholars from various disciplines at home and abroad have conducted research on the impact mechanisms under plant communities and biological crust cover, achieving many important results. For instance, the research by Cao Yousong's team demonstrated that the symbiotic action of biological soil crusts and plant communities, through the biological activities of roots and biological crusts, collectively promotes the improvement of soil structure and the reduction of soil erosion. This emphasizes the importance of plant communities and biological soil crusts in soil protection and ecological restoration in cold-winter arid regions, providing a new perspective on the role of biological soil crusts under different environmental conditions [29]. Dou Weiqiang's team revealed the regulatory role of biological soil crusts in the soil carbon cycle within semi-arid desert ecosystems, offering a new perspective on the ecological functions of biological soil crusts in arid and semi-arid regions. This has significant implications for regional carbon flux estimation and the feedback of terrestrial ecosystems to global climate change [30,31]. Fick's team highlighted the role of biological soil crusts in improving soil stability and hydrological functions, particularly emphasizing the importance of rapid induction and management of biological soil crusts for soil protection and ecological restoration in arid and semi-arid ecosystems [32]. Zhang Jing's team proposed a new perspective on the interaction between biological soil crusts and vegetation, emphasizing the multifunctional roles of biological soil crusts within ecosystems, including improving soil quality, increasing soil organic carbon content, and promoting vegetation recovery. This provides new insights into the control of soil and water loss on the Loess Plateau, emphasizing the potential of biological soil crusts in ecological restoration and land management, especially in arid and semi-arid areas [33]. While significant advancements have been achieved in soil and water conservation research, the understanding of the synergistic effects of biological soil crusts and plant community symbiosis patterns on these conservation efforts remains limited. In particular, investigations into how biological soil crusts and plant communities collaboratively contribute to soil and water conservation outcomes in the ecologically fragile region of central Ningxia are still insufficient. Current research has predominantly focused on individual factors, lacking a comprehensive exploration of the integrated effects of biological soil crusts and plant community symbiosis patterns [34].

Research on biological crusts [35–37] in the ecologically fragile area of central Ningxia has revealed their important roles in fixing sand dunes, improving soil quality, promoting water retention, and protecting biodiversity. With further research and application, biological crusts are expected to become an effective tool for improving the ecological environment in arid areas, preventing desertification, and promoting sustainable development [38–40]. In this study, we investigated the soil and water conservation effects of various symbiotic patterns between plant communities and biological crusts using artificial rainfall simulation in the field. Our aim was to evaluate the conservation potential of these symbiotic patterns in the ecologically fragile region of central Ningxia and to provide a theoretical foundation for understanding hydrological processes as well as soil and water conservation strategies in this area. We hypothesized that specific symbiotic configurations of plant communities and biological crusts could effectively enhance soil erosion resistance while reducing runoff and sediment loss. The results indicated that certain combinations of plant communities and biocrusts exhibited significant advantages in mitigating slope runoff and sediment loss; these symbiotic modes notably decreased both runoff volume and sediment concentration, thereby improving soil moisture retention capacity. This study offers scientific management strategies and practical guidance for soil and water conservation efforts in the

ecologically vulnerable areas of central Ningxia, highlighting the importance of promoting these symbiotic models within the region.

## 2. Materials and Methods

### *2.1. Study Area*

The study area is located in the Baijitan Nature Reserve in Ningxia. The reserve is situated in the central arid zone of Ningxia, at the southwestern edge of the Mu Us Desert (37°49′05″–38°20′54″ N, 106°20′22″–106°37′19″ E). It is one of the earlier established desert-type reserves, with an area of 748.43 $km^2$ and an elevation of 1150–1650 m. The natural reserve falls within the mid-temperate arid climate zone, characterized by severe winters, dry and hot summers, with an average temperature of 10.4 °C and an annual average precipitation of 197.6 mm. However, the distribution of precipitation within the year is uneven, with the majority falling between June and August, accounting for about 60% of the annual total. The evaporation rate is high, with an average annual evaporation of 1929.8 mm, which is 9.8 times the amount of rainfall. The main soil types in the study area are gray calcium soil and aeolian sandy soil, which have relatively loose structures. The main vegetation includes sandy desert plants, annual herbaceous plants, and desert vegetation. Representative plants include *Artemisia argyi H.Lév & Vaniot*, *Artemisia deserti Krasch.*, *Artemisia selengensis Turcz. ex Besser*, *Caragana korshinskii Kom.*, *Sophora alopecuroides L.*, *Calligonum mongolicum Turcz.*, and *Hedysarum scoparium Fisch. & C.A. Mey*. The dominant species of algal crust and moss crust in the study area are *Microcoleus vaginatus Gomont* and *Bryum argenteum Hedw.*, respectively [41].

### *2.2. Experimental Methods*

In order to clarify the relationship between the effects of different plant communities and biological crust symbiosis on soil erosion and its composition, 8 treatments and 1 blank control group were set up (Table 1). In July 2024, simulated rainfall experiments were conducted for quantitative research on soil erosion, which is widely applied in the study of soil erosion mechanisms. The artificial simulated rainfall device mainly consisted of a nozzle, steel pipe, pressure gauge, regulating valve, water pump, and steel support. According to the heavy rain standard in Ningxia region, a duration of 30 min with rainfall of more than 50 mm is considered a severe storm. The experimental design rainfall intensity was set at 90 $mm \cdot h^{-1}$, with a rainfall duration of 90 min. All treatments were repeated three times.

### *2.3. Measurement Items and Methods*

The bulk density of the soil layer beneath the biological crust was measured using a core cutter method; the amount of sediment was measured using a drying method. During the experiment, the initial moisture content and post-rain moisture content of the soil in the simulated rainfall device were determined by TDR instrument (TRIME-T3 TDR measurement system produced by KOMAX company in Bad Konstadt, Germany).

The design parameters for the simulated rainfall experiment are shown in Table 2.

The simulated rainfall experiment began from the start of runoff (when a continuous flow of water formed at the outlet) and lasted for 90 min. A sediment runoff sample was collected every 10 min. A collection trough was set at the bottom of the device to ensure that all runoff within the plot was collected into a runoff bucket placed at the outlet. During the rainfall, potassium permanganate was used to measure the time taken for runoff to flow over a 0.5 m slope section, to calculate the runoff velocity. After the rainfall, the runoff volume and sediment amount were measured. Both runoff volume and sediment amount measurements were conducted according to the "Soil and Water Conservation Test Procedures" [42].

**Table 1.** Basic information of sample plots.

| Sample Plot Number | Treatment | | Vegetation Cover (%) | Crust Coverage (%) | Crust Thickness (mm) | Initial Moisture Content (%) | Post-Rain Moisture Content (%) | Uniformity Coefficient. (CU) | Bray–Curtis Similarity Index | Purpose of Sample Plot Design |
|---|---|---|---|---|---|---|---|---|---|---|
| Sample plot 1 | No Vegetation | Mixed Crust | 0 | 49 | 6.11 | 1.26 | 8.26 | 90.2 | 0.2 | Biological crust control |
| Sample plot 2 | *A. argyi* | Mixed Crust | 31 | 51 | 6.17 | 1.36 | 8.41 | 89.6 | 0.3 | Symbiosis between a single herbaceous plant and biological crusts |
| Sample plot 3 | *A. selengensis* | Mixed Crust | 29 | 50 | 6.25 | 1.34 | 8.37 | 91.3 | 0.3 | Symbiosis between a single herbaceous plant and biological crusts |
| Sample plot 4 | *C. mongolicum* | Mixed Crust | 30 | 48 | 5.94 | 1.58 | 8.51 | 90.5 | 0.3 | Perennial shrubs and biological crust symbiosis |
| Sample plot 5 | *A.argyi*, *A. selengensis* | Mixed Crust | 32 | 52 | 5.96 | 1.46 | 8.33 | 92.1 | 0.45 | Multiple herbaceous plants coexist with biological crusts |
| Sample plot 6 | *A.argyi*, *C. mongolicum* | Mixed Crust | 29 | 50 | 6.31 | 1.62 | 8.53 | 91.9 | 0.45 | Symbiosis between herbaceous plants, shrubs, and biological crusts |
| Sample plot 7 | *A. selengensis*, *C. mongolicum* | Mixed Crust | 31 | 51 | 5.99 | 1.49 | 8.43 | 89.2 | 0.45 | Symbiosis between herbaceous plants, shrubs, and biological crusts |
| Sample plot 8 | *A.argyi*, *A. selengensis*, *C. mongolicum* | Mixed Crust | 30 | 49 | 6.28 | 1.63 | 8.63 | 90.5 | 1 | Multiple herbaceous plants, shrubs, and biological crusts coexist in symbiosis |
| Sample plot 9 | No Vegetation | No Crust | 0 | 0 | 0 | 1.09 | 7.26 | 89.1 | 0 | Blank control |

Note: All data presented in the table are averages obtained from three replicates.

**Table 2.** Design parameters for soil trough rainfall simulation experiment.

| Parameter | Value | Unit | Notes |
|---|---|---|---|
| Soil Trough Dimensions | 100 × 100 × 20 | cm | Length, width, and depth of the soil trough. |
| Bulk Density | 1.30 | $g/cm^3$ | Bulk density of the soil used to simulate natural soil conditions. |
| Slope | 30 | degrees | Slope setting of the soil trough. |
| Rainfall Intensity | 90 | $mm \cdot h^{-1}$ | Rainfall intensity set for the experiment. |
| Rainfall Duration | 90 | minutes | Duration of each rainfall event. |
| Replicates | 3 | times | Number of replicates for each treatment to ensure data reliability. |
| Sampling Location | 1 m from the boundary | meters | Sampling location chosen to avoid damaging the soil surface. |
| Sampling Depth | 20 | cm | Sampling depth to ensure sufficient soil sample collection. |
| Soil Filling Method | Uniform layering | - | Soil is filled in uniform layers to ensure consistency with natural soil conditions. |
| Bulk Density Range | 1.16–1.35 | $g/cm^3$ | Range of bulk density controlled during soil filling. |
| Rainfall Uniformity Coefficient | >85 | - | Uniformity coefficient of each rainfall event to ensure even and accurate rainfall. |

### *2.4. Data Processing*

Data analysis was conducted using Excel 2016. Differences in plant communities and biotic crust symbiosis patterns among various plots were compared utilizing the Bray–Curtis Similarity Index. One-way analysis of variance (ANOVA) was performed with IBM SPSS Statistics 26.0 to assess the soil and water conservation effects of different plant communities and biological crust symbiosis patterns, followed by significance testing using the least significant difference (LSD) method ($\alpha = 0.05$). The data presented in tables represent means, while graphical representations display means ± standard error. Graphical illustrations were created using Origin Pro 2022 software (Version number: 9.900220).

## 3. Results

### *3.1. The Impact of the Plant Communities and Biological Crust Symbiosis Patterns on Slope Runoff Characteristics*

As shown in Table 3, under a rainfall intensity of 90 $mm \cdot h^{-1}$, the initial runoff time on slopes varies significantly under different plant communities and biological crust symbiosis patterns, with the initial runoff time extending as the type of plant community and the coverage of biological crust increase. Plot 9 (bare land) has the shortest initial runoff time of 0.9 min; the slope under the treatment of the symbiosis pattern of *A. argyi*, *A. selengensis* and *C. mongolicum* communities with 30% mixed crust (Plot 8) has the longest initial runoff time of 7.6 min. This indicates that different plant communities and biological crust symbiosis patterns can effectively prolong the initial runoff time on slopes of eroded and degraded lands, and the effect is most significant with *A. argyi*, *A. selengensis*, and *C. mongolicum.* combined with 30% mixed crust. Under different plant communities and biological crust symbiosis patterns, the peak runoff is reduced to varying degrees compared to Plot 9 (bare land). This synergistic effect significantly delays the formation of peak slope runoff. Specifically, the interaction between plant roots and biological crusts strengthens soil consolidation, improves soil stability, and enhances its water retention properties. These improvements help to reduce the infiltration rate of rainwater and surface runoff velocity, thereby delaying the time at which slope runoff reaches its maximum flow.

**Table 3.** Characteristics of runoff generation on slopes with various plant communities and biological soil crust symbiosis patterns.

| Sample Plot Number | Initial Runoff Time (min) | Peak Runoff ($L \cdot min^{-1}$) | Time to Peak (min) |
|---|---|---|---|
| Sample plot 1 | 1.2 | 1.13 | 10 |
| Sample plot 2 | 2.5 | 1.07 | 10 |
| Sample plot 3 | 1.8 | 0.98 | 10 |
| Sample plot 4 | 2.9 | 0.76 | 10 |
| Sample plot 5 | 3.6 | 0.55 | 10 |
| Sample plot 6 | 5.2 | 0.28 | 80 |
| Sample plot 7 | 4.1 | 0.51 | 60 |
| Sample plot 8 | 7.6 | 0.17 | 80 |
| Sample plot 9 | 0.9 | 1.44 | 10 |

Note: All data presented in the table are averages obtained from three replicates.

As can be seen from Figure 1, there is a significant difference in slope runoff volume under different plant communities and biological crust symbiosis patterns. The slope runoff volumes are in the order of Plot 8, Plot 6, Plot 7, Plot 5, Plot 4, Plot 2, Plot 3, Plot 1, Plot 9. The slope runoff volume is the smallest on bare land (Plot 9); the slope under the treatment of *A. argyi*, *A. selengensis*, and *C. mongolicum* communities with biological crust symbiosis (Plot 8) has the largest runoff volume. As the rainfall duration increases, the cumulative runoff volume on each slope continues to grow. Ranking the slope cumulative runoff volume by size, the treatment under different plant communities and biological crust symbiosis patterns also shows Plot 8, Plot 6, Plot 7, Plot 5, Plot 4, Plot 2, Plot 3, Plot 1, Plot 9. The cumulative runoff volume on the bare slope (Plot 9) is 6.29 times that of the slope under the treatment of *A. argyi*, *A. selengensis*, and *C. mongolicum* communities with biological crust symbiosis (Plot 8). Under a rainfall intensity of 90 $mm \cdot h^{-1}$, the *A. argyi*, *A. selengensis*, and *C. mongolicum.* communities with 30% mixed crust symbiosis pattern have the most significant effect on reducing runoff on slopes.

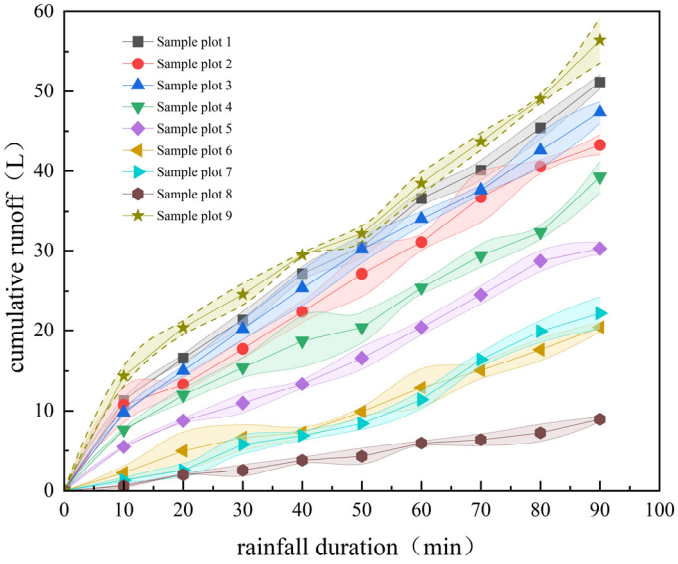



**Figure 1.** Dynamics of slope runoff under different plant assemblages and biological soil crust symbiosis with rainfall duration. Note: The stripes in the figure represent the standard error.

### *3.2. The Impact of Different Plant Communities and Biological Crust Symbiosis Patterns on Slope Sediment Yield Characteristics*

As can be seen from Figure 2, under a rainfall intensity of 90 $mm \cdot h^{-1}$, there is a significant difference in the sediment concentration of runoff on slopes under different plant communities and biological crust symbiosis patterns, with the sediment concentration decreasing as the type of plant community and the coverage of biological crust increase. Throughout the entire rainfall process, the sediment concentration in the runoff on each slope fluctuates significantly, increasing before 40 min and decreasing after 40 min. The

sediment concentrations from smallest to largest are Plot 8, Plot 6, Plot 7, Plot 5, Plot 4, Plot 2, Plot 3, Plot 1, and Plot 9 (bare land). This indicates that different plant communities and biological crust symbiosis patterns can effectively reduce the intensity of slope erosion, decrease the sediment concentration in runoff, and retain water and soil. The effect is most significant with *A. argyi*, *A. selengensis*, and *C. mongolicum.* combined with 30% mixed crust.

Throughout the entire rainfall process, the cumulative sediment yield under both single plant community and biological crust symbiosis pattern treatments and multiple plant community and biological crust symbiosis pattern treatments is lower than that of the bare land control. As the variety of plant communities and the coverage of biological crust increase, the cumulative sediment amount gradually decreases (Figure 3). The cumulative sediment yield on the nine slopes is in the order of Plot 8, Plot 6, Plot 7, Plot 5, Plot 4, Plot 2, Plot 3, Plot 1, Plot 9, with the largest cumulative sediment yield on the bare land (Plot 9). The cumulative sediment yield under the treatment of *A. argyi*, *A. selengensis*, and *C. mongolicum.* communities with biological crust symbiosis (Plot 8) is relatively low. By the end of the rainfall, the cumulative sediment yield on the bare slope (Plot 9) is 31.5 times that of the slope under the treatment of *A. argyi*, *A. selengensis*, and *C. mongolicum* communities with biological crust symbiosis (Plot 8). After the completion of the simulated rainfall experiment, we compared the cumulative sediment yield of different treatment plots (Plots 1–8) with that of the bare land treatment (Plot 9). The results show that: For Plot 1, the cumulative sediment yield decreased by 21.4%. For Plot 2, the cumulative sediment yield decreased by 43.85%. For Plot 3, the cumulative sediment yield decreased by 32.73%. For Plot 4, the cumulative sediment yield decreased by 58.74%. For Plot 5, the cumulative sediment yield decreased by 73.75%. For Plot 6, the cumulative sediment yield decreased by 88.57%. For Plot 7, the cumulative sediment yield decreased by 87.15%. For Plot 8, the cumulative sediment yield decreased by 96.82%. This indicates that the root structures of different plant communities can penetrate deep into the soil, increasing soil stability and reducing the sediment concentration in runoff. The coverage of biological crust, on top of the plant communities, more effectively weakens the intensity of slope erosion, slows down the runoff velocity, and reduces the sediment concentration in runoff. Under a rainfall intensity of 90 mm·h$^{-1}$, the *A. argyi*, *A. selengensis*, and *C. mongolicum.* communities with 30% mixed crust symbiosis pattern coverage have a significant effect on reducing soil erosion and can significantly affect the slope sediment yield process.

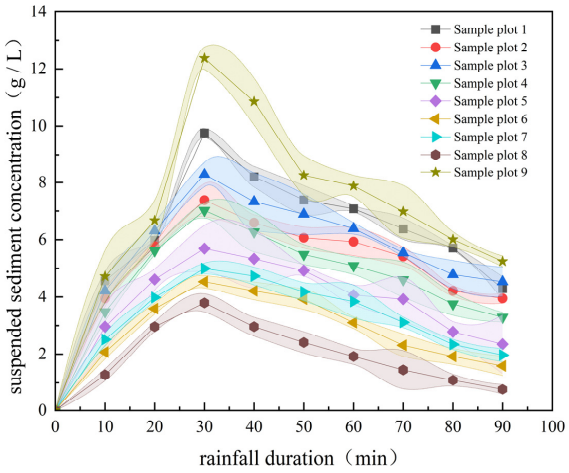



**Figure 2.** The characteristics of sediment concentration variation in runoff under different plant community and biological crust symbiotic patterns on slopes. Note: The stripes in the figure represent the standard error.

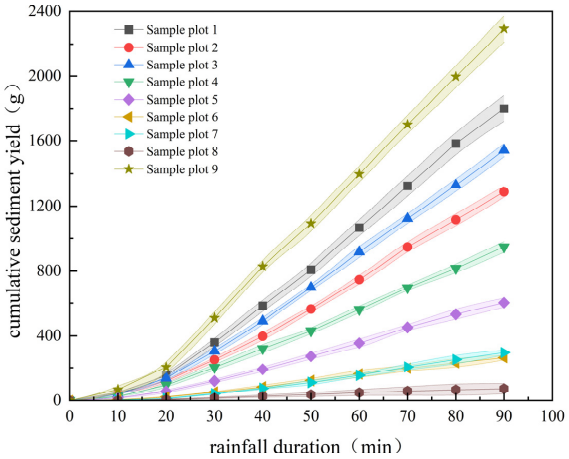



**Figure 3.** The characteristics of cumulative sediment yield variation on slopes under different plant community and biological crust symbiotic patterns. Note: The stripes in the figure represent the standard error.

## 4. Discussion

### *4.1. The Impact of Different Plant Communities and Biological Soil Crusts on the Characteristics of Slope Runoff Generation*

The initial runoff time on a slope reflects the speed at which runoff begins to form and is a key indicator for measuring the slope runoff generation process. It reveals how easy or difficult it is for runoff to begin on the slope [43]. The slope under the treatment of the *A. argyi*, *A. selengensis*, and *C. mongolicum* communities with biological crust symbiosis (Plot 8) has the lowest peak runoff and effectively delays the time of peak runoff, with the peak runoff being only 11.81% of that of the bare land (Plot 9). This demonstrates that the coverage of plant communities and biological crust symbiosis patterns is crucial for enhancing the structural stability and water retention capacity of the soil. Under the same rainfall conditions, changes in the underlying surface can lead to differences in runoff time. The water-absorbing properties of biological soil crusts, along with their capacity to improve soil texture, increase porosity, and enhance organic matter content, contribute to the enhancement of moisture retention in slopes, thereby delaying the onset of runoff formation [44].

The formation of biological soil crusts can significantly improve soil structure and increase soil porosity and organic matter content, thereby enhancing the soil's moisture retention capacity [45]. This improved soil structure helps water to penetrate and be stored in the soil more effectively, reducing the generation of surface runoff. At the same time, the water-absorbing properties of biological soil crusts also directly increase the soil's water storage capacity, further reducing runoff speed and volume. Plant communities also positively affect the physical properties of the soil through their network of roots. Roots can stabilize soil particles, reduce erosion, and promote both vertical and horizontal water infiltration. Different types of plant communities, such as herbaceous plants, shrubs, or trees, have different effects on soil moisture regulation due to their root depth and distribution patterns [46]. For example, deep-rooted plants can promote the use and storage of deep soil moisture, while shallow-rooted plants mainly affect the moisture conditions of the surface soil.

In natural ecosystems, the symbiotic patterns of plant communities and biological soil crusts have a significant impact on the slope hydrological process, especially in regulating the cumulative runoff volume of slopes. On the one hand, the combined effects of biological soil crusts and plant roots increase the soil's moisture retention capacity, reducing the generation of runoff; on the other hand, they also improve the soil's permeability, allowing more precipitation to enter the soil rather than forming surface runoff [47]. This impact is particularly evident during rainfall events, effectively delaying the formation time of

slope runoff peaks and reducing the risk of flooding. In addition, the diversity of plant communities and their interactions with biological soil crusts can also enhance the overall stability of slope ecosystems, increasing their resistance to extreme climate events. The symbiotic relationship between plant communities and biological soil crusts significantly influences slope hydrological processes. Quantitative studies have shown that biological soil crusts, through their water-absorbing properties and soil structure improvement, significantly reduce runoff and sediment loss while enhancing soil infiltration rates and water retention capacity. Long-term monitoring, as evidenced by a comprehensive review of relevant literature, indicates that areas covered by biological soil crusts exhibit more stable soil moisture dynamics, which helps maintain soil moisture and resist drought conditions. These findings collectively highlight the critical role of biological soil crusts in promoting slope hydrological balance and reducing soil erosion, providing robust scientific support for ecological restoration and soil and water conservation efforts.

### *4.2. The Impact of Different Plant Communities and Symbiotic Patterns of Biological Soil Crusts on Slope Sediment Yield Characteristics*

Under the condition of a rainfall intensity of 90 mm/h, the symbiotic treatment of *A. argyi*, *A. selengensis*, and *C. mongolicum* with biological crust showed the best sand reduction effect compared to other treatment modes, because they have deep root, shallow root plants, and a biological crust, which resist soil erosion under the combined action of multiple factors and have good recovery performance. Various plant communities and symbiotic patterns of biological soil crusts significantly reduce the sediment concentration and cumulative sediment yield of runoff on slopes. The presence of plant communities and biological soil crusts can improve soil physical and chemical properties, increase soil cohesion, and the rhizoids and hyphae of moss crusts, as well as the polysaccharides secreted by algal crusts, can consolidate the soil, reduce the direct impact of raindrops on the surface soil, and enhance the soil's resistance to erosion [48,49]. Under their protection, the underlying soil is prevented from the impact of raindrops and resists the detachment of soil particles by surface runoff. Different plant communities have significantly different root structures; deep-rooted plants (such as *C. mongolicum* and certain trees and shrubs) can penetrate deep into the soil, increasing soil stability and reducing the sediment concentration in runoff [50]. In contrast, shallow-rooted plants (such as *Artemisia* and other herbaceous plants) may have a smaller stabilizing effect on the soil surface. The higher the vegetation coverage, the more effectively the stems and leaves of plants can intercept raindrops, reducing the direct impact of raindrops on the soil surface, thereby lowering the sediment concentration in runoff [51]. The development degree of biological soil crusts also affects their protective effect on the soil [52–54]. Mature biological soil crusts usually have higher soil cohesion and better water retention capacity, thus more effectively reducing the sediment concentration in runoff. The presence of plant communities and biological soil crusts usually slows down the runoff velocity, thereby reducing the erosion effect of runoff on the soil and lowering the sediment concentration in runoff. On bare soil without vegetation and biological soil crust cover, rainfall can easily cause higher soil erosion, leading to an increase in the sediment concentration in runoff; conversely, soil with good coverage of vegetation communities and biological soil crust usually has a lower sediment concentration in runoff [55,56].

Plant communities can enhance soil structure through the growth and decay of their root systems, while biological crusts may increase soil organic matter content via their biological activities. The interaction between these two factors could produce a synergistic effect on slope runoff and sediment yield. These impacts are influenced by environmental variables such as rainfall intensity, soil type, terrain slope, plant species, and biological crust coverage. Understanding the role of biological crusts in slope hydrology and erosion processes is essential for providing a scientific basis for land management in arid and semi-arid regions. By promoting vegetation restoration and cultivating biological crusts, it is possible to effectively reduce sediment content and cumulative sediment yield in runoff, minimize soil erosion, and enhance soil and water conservation.

### *4.3. The Impact of Different Plant Communities and Biotic Crust Symbiosis Patterns on Ecosystem Sustainability*

In arid and semi-arid regions, soil erosion and land degradation are increasingly severe, posing a significant threat to ecosystem sustainability. In this context, diverse plant communities and symbiotic models involving biological crusts play a crucial role as they collaboratively employ multiple mechanisms to effectively control soil erosion, promote ecological restoration, and enhance the resilience of ecosystems.

The physical protective effects of plant roots and biological crusts mitigate wind and water erosion. The protective layer formed by biological crusts diminishes the direct impact of raindrops on the soil while enhancing its water absorption and retention capacity, thereby reducing surface runoff. The synergistic activity of plant roots and biological crusts also improves soil structure, increases the stability of soil aggregates, and consequently enhances resistance to erosion. Furthermore, as 'ecological engineers', biological crusts create suitable environments for seed germination and seedling growth, promote natural vegetation restoration, and support greater biodiversity by providing habitats and food sources for various organisms. By facilitating processes such as soil formation and nutrient cycling, plant communities alongside biological crusts contribute to restoring essential ecosystem functions like carbon fixation and nitrogen cycling. The symbiotic relationship between plant communities and biological crusts optimizes resource utilization efficiency, reduces reliance on external inputs, and bolsters ecosystem resilience against climate change impacts as well as other environmental pressures, ultimately achieving long-term ecological stability and sustainability. To fully leverage these symbiotic patterns requires in-depth research coupled with practical applications; scientific investigations should focus on elucidating the ecological mechanisms underlying different symbiotic patterns along with their long-term effects to provide a robust foundation for formulating effective ecological restoration strategies.

In this study, the three plant communities of *A. argyi*, *A. selengensis*, and *C. mongolicum* showed significant effects on soil erosion control, ecological restoration, and sustainability in the vulnerable areas of central Ningxia under the symbiotic mode of biological crust. Through in-depth research and rational application of these symbiotic modes, we can more effectively address soil erosion and land degradation issues in arid and semi-arid regions, and promote the sustainability of ecosystems. Future research should further explore the ecological mechanisms and long-term effects of different symbiotic patterns, in order to provide more comprehensive scientific support for ecological restoration and sustainable development.

## 5. Conclusions

This study, through artificial rainfall experiments conducted on different plant communities and biological soil crust symbiosis patterns in the ecologically fragile region of central Ningxia, preliminarily revealed that these symbiosis patterns have a positive effect on erosion resistance and soil and water conservation in the area. The main conclusions are as follows:

(1) Under a rainfall intensity of 90 $mm \cdot h^{-1}$, the initial runoff time on each slope was significantly positively correlated with the type of plant community and the coverage of biological soil crusts, extending as the diversity of plant communities and the coverage of biological soil crusts increased. The treatment with a symbiotic pattern of *A. argyi*, *A. selengensis*, and *C. mongolicum.* communities and mixed biological soil crusts (Plot 8) achieved the best results.

(2) The cumulative runoff volume on each slope increased with the extension of rainfall duration. The treatment with a symbiotic pattern of *A. argyi*, *A. selengensis*, and *C. mongolicum* communities and mixed crusts (Plot 8) had the most significant effect in reducing runoff on slopes.

(3) The sediment concentration in runoff varied significantly among slopes with different plant community and biological soil crust symbiotic patterns, decreasing as the

diversity of plant communities and the coverage of biological soil crusts increased. Throughout the rainfall, the sediment concentration in runoff fluctuated, initially increasing until 40 min and decreasing thereafter.

(4) The cumulative sediment yield under both single plant community and biological soil crust symbiotic patterns and multiple plant community and biological soil crust symbiotic patterns was lower than that of the bare land control. With the increase in plant community diversity and biological soil crust coverage, the cumulative sediment yield gradually decreased. The treatment with a symbiotic pattern of *A. argyi*, *A. selengensis*, and *C. mongolicum* communities and mixed crusts had a significant effect in reducing soil erosion, which could markedly influence the sediment yield process on slopes.

In conclusion, this study underscores the significance of various plant communities and biological soil crust symbiotic patterns in collectively influencing the characteristics of slope runoff and sediment yield through multiple mechanisms. It highlights the potential of plant community diversity and biological soil crust coverage in alleviating runoff and sediment yield and promoting ecological restoration in fragile ecosystems. The results indicate a significant impact on slope soil erosion, which in turn affects the hydrological cycle and ecological restoration of the entire ecologically fragile area. This study provides valuable insights for the scientific assessment and implementation of three-dimensional ecological restoration systems that leverage the synergistic effects of plant communities and biological soil crusts. Future research could further explore the long-term impacts of these symbiotic patterns on soil erosion resistance and ecological restoration, contributing to the goals of ecological sustainability in vulnerable environments.

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## References

1. Li, X.-R.; Jia, R.-L.; Zhang, Z.-S.; Zhang, P.; Hui, R. Hydrological response of biological soil crusts to global warming: A ten-year simulative study. *Glob. Chang. Biol.* **2018**, *24*, 4960–4971. [CrossRef] [PubMed]
2. Pietrasiak, N.; Regus, J.U.; Johansen, J.R.; Lam, D.; Sachs, J.L.; Santiago, L.S. Biological soil crust community types differ in key ecological functions. *Soil Biol. Biochem.* **2013**, *65*, 168–171. [CrossRef]
3. Song, G.; Li, X.; Hui, R. Effect of biological soil crusts on seed germination and growth of an exotic and two native plant species in an arid ecosystem. *PLoS ONE* **2017**, *12*, e0185839. [CrossRef]
4. Weber, B.; Belnap, J.; Budel, B.; Antoninka, A.J.; Barger, N.N.; Chaudhary, V.B.; Darrouzet-Nardi, A.; Eldridge, D.J.; Faist, A.M.; Ferrenberg, S.; et al. What is a biocrust? A refined, contemporary definition for a broadening research community. *Biol. Rev.* **2022**, *97*, 1768–1785. [CrossRef]
5. Li, B.; Gao, J.; Wang, X.; Ma, L.; Cui, Q.; Vest, M. Effects of biological soil crusts on water infiltration and evaporation Yanchi Ningxia, Maowusu Desert, China. *Int. J. Sediment Res.* **2016**, *31*, 311–323. [CrossRef]
6. Zheng, J.; Peng, C.; Li, H.; Li, S.; Huang, S.; Hu, Y.; Zhang, J.; Li, D. The role of non-rainfall water on physiological activation in desert biological soil crusts. *J. Hydrol.* **2018**, *556*, 790–799. [CrossRef]
7. Ferrenberg, S.; Tucker, C.L.; Reed, S.C. Biological soil crusts: Diminutive communities of potential global importance. *Front. Ecol. Environ.* **2017**, *15*, 160–167. [CrossRef]
8. Maestre, F.T.; Bowker, M.A.; Escolar, C.; Puche, M.D.; Soliveres, S.; Maltez-Mouro, S.; Garcia-Palacios, P.; Castillo-Monroy, A.P.; Martinez, I.; Escudero, A. Do biotic interactions modulate ecosystem functioning along stress gradients? Insights from semi-arid plant and biological soil crust communities. *Philos. Trans. R. Soc. B-Biol. Sci.* **2010**, *365*, 2057–2070. [CrossRef]

9. Chamizo, S.; Rodriguez-Caballero, E.; Canton, Y.; Asensio, C.; Domingo, F. Penetration resistance of biological soil crusts and its dynamics after crust removal: Relationships with runoff and soil detachment. *Catena* **2015**, *126*, 164–172. [CrossRef]
10. Zhao, Y.; Qin, N.; Weber, B.; Xu, M. Response of biological soil crusts to raindrop erosivity and underlying influences in the hilly loess plateau region, China. *Biodivers. Conserv.* **2014**, *23*, 1669–1686. [CrossRef]
11. Faist, A.M.; Herrick, J.E.; Belnap, J.; Van Zee, J.W.; Barger, N.N. Biological soil crust and disturbance controls on surface hydrology in a semi-arid ecosystem. *Ecosphere* **2017**, *8*, e01691. [CrossRef]
12. Chen, B.; Yang, X.; Jiang, Q.; Liang, P.; Mackenzie, L.L.; Zhou, Y. Geochemistry of aeolian sand in the Taklamakan Desert and Horqin Sandy Land, northern China: Implications for weathering, recycling, and provenance. *Catena* **2022**, *208*, 105769. [CrossRef]
13. Xu, X.; Liu, J.; Qiu, J.; Zhang, K.; Jiao, F.; Lin, D.; Yang, Y.; Lin, N.; Zou, C. Comparison of nonlinear trends and influencing factors of carbon sinks in four ecological restoration projects in China. *Land Degrad. Dev.* **2024**, *35*, 3062–3074. [CrossRef]
14. Buedel, B.; Colesie, C.; Allan Green, T.G.; Grube, M.; Lazaro Suau, R.; Loewen-Schneider, K.; Maier, S.; Peer, T.; Pintado, A.; Raggio, J.; et al. Improved appreciation of the functioning and importance of biological soil crusts in Europe: The soil crust international project (SCIN). *Biodivers. Conserv.* **2014**, *23*, 1639–1658. [CrossRef]
15. Buedel, B.; Darienko, T.; Deutschewitz, K.; Dojani, S.; Friedl, T.; Mohr, K.I.; Salisch, M.; Reisser, W.; Weber, B. Southern african biological soil crusts are ubiquitous and highly diverse in drylands, being restricted by rainfall frequency. *Microb. Ecol.* **2009**, *57*, 229–247. [CrossRef]
16. Wang, Y.; Li, X.; Wu, X.; Hong, Y.; Wang, T.; Zuo, F.; Zhang, J.; Yang, X. Divergent effects of biological soil crusts on soil respiration between bare patches and shrub patches under simulated rainfall in a desert ecosystem in northwest China. *Soil Tillage Res.* **2021**, *214*, 105185. [CrossRef]
17. Aslam, S.N.; Dumbrell, A.J.; Sabir, J.S.; Mutwakil, M.H.Z.; Baeshen, M.M.N.; Abo-Aba, S.E.M.; Clark, D.R.; Yates, S.A.; Baeshen, N.A.; Underwood, G.J.C.; et al. Soil compartment is a major determinant of the impact of simulated rainfall on desert microbiota. *Environ. Microbiol.* **2016**, *18*, 5048–5062. [CrossRef]
18. Dan, C.; Liu, G.; Zhang, Q.; Zhao, Y.; Shen, E.; Liu, C.; Liu, Y.; Shu, C.; Xia, X.; Liu, D.; et al. The coupling effects of grass and shrub with biological crust on the overland flow hydrodynamic characteristics. *Catena* **2024**, *245*, 108281. [CrossRef]
19. Xu, H.; Zhang, Y.; Kang, B.; Qin, F.; Liu, X.; Zhou, H.; Shao, X. Different types of biocrusts affect plant communities by changing the microenvironment and surface soil nutrients in the Qinghai-Tibetan plateau. *Arid Land Res. Manag.* **2020**, *34*, 306–318. [CrossRef]
20. Xie, S.Q.; Gao, L.Q.; Zhao, Y.G.; Guo, Y.W. Responses of runoff and soil loss from biological soil crustal slope to rainfall intensity under simulated rainfall. *Ying Yong Sheng Tai Xue Bao = J. Appl. Ecol.* **2019**, *30*, 391–397. [CrossRef]
21. Xu, L.; Li, X.; Tang, X.; Kou, Y.; Li, C.; Li, J.; Yao, M.; Zhang, B.; Wang, L.; Xu, H.; et al. Consistent community assembly but contingent species pool effects drive β-diversity patterns of multiple microbial groups in desert biocrust systems. *Mol. Ecol.* **2024**, *33*, e17386. [CrossRef] [PubMed]
22. Xu, W.; Zhao, Y.; Lian, Y.; Zhao, Y.; Zhang, Z. Co-development of biocrust and herbaceous plant communities in sandy areas after cyanobacterial inoculation. *Plant Soil* **2024**. [CrossRef]
23. Yuan, M.; Xiao, H.; Wang, R.; Duan, Y.; Cao, Q. Effects of changes in precipitation pattern and of seaweed fertilizer addition on plant traits and biological soil crusts. *J. Appl. Phycol.* **2019**, *31*, 3791–3802. [CrossRef]
24. Zhan, J.; Yang, G.-D.; Sun, Q.-Y. Diversity of nitrogen-fixing microorganisms in biological soil crusts of copper mine wastelands. *Ying Yong Sheng Tai Xue Bao = J. Appl. Ecol.* **2014**, *25*, 1765–1772.
25. Chen, G.; Chang, C.; He, X.-B.; Zhang, Q.-W.; Li, M.; Wang, J.; Geng, R.; Qiao, J.-B.; Zhang, F.-B.; Wang, H. Variations in microbial characteristics of overland flow from steep slopes with biocrusts during rainfall in a semiarid region. *J. Hydrol.* **2024**, *635*, 131158. [CrossRef]
26. Papatheodorou, E.M.; Papapostolou, A.; Monokrousos, N.; Jones, D.W.; Scullion, J.; Stamou, G.P. Crust cover and prior soil moisture status affect the response of soil microbial community and function to extreme rain events in an arid area. *Eur. J. Soil Biol.* **2020**, *101*, 103243. [CrossRef]
27. Qi, J.; Li, X.; Jia, R.; Yang, H.; Shi, Y.; Sun, J.; Fu, T. Response of biocrust nitrogenase activity to the variation of rainfall regime in the Tengger Desert, northern China. *Catena* **2022**, *212*, 106093. [CrossRef]
28. Fick, S.E.; Belnap, J.; Duniway, M.C. Grazing-induced changes to biological soil crust cover mediate hillslope erosion in long-term exclosure experiment. *Rangel. Ecol. Manag.* **2020**, *73*, 61–72. [CrossRef]
29. Cao, Y.; Xiao, B.; Ghanbarian, B. Biocrusts enhance soil structural stability during freeze-thaw cycles and improve soil erosion resistance in cold-winter drylands. *Catena* **2024**, *243*, 108206. [CrossRef]
30. Dou, W.; Xiao, B.; Yao, X.; Kidron, G.J. Asymmetric responses of biocrust respiration to precipitation manipulation under a changing semiarid climate. *Geoderma* **2023**, *430*, 116318. [CrossRef]
31. Dou, W.; Xiao, B.; Revillini, D.; Delgado-Baquerizo, M. Biocrusts enhance soil organic carbon stability and regulate the fate of new-input carbon in semiarid desert ecosystems. *Sci. Total Environ.* **2024**, *918*, 170794. [CrossRef] [PubMed]
32. Fick, S.E.; Barger, N.N.; Duniway, M.C. Hydrological function of rapidly induced biocrusts. *Ecohydrology* **2019**, *12*, e2089. [CrossRef]
33. Zhang, J.; Liu, Y.; Hou, F. Changes in vegetation and soil coupling induced by biocrusts: New thinking on the segmented control of soil and water loss in the loess plateau, China. *Ecol. Indic.* **2024**, *161*, 111953. [CrossRef]

34. Chandler, D.G.; Day, N.; Madsen, M.D.; Belnap, J. Amendments fail to hasten biocrust recovery or soil stability at a disturbed dryland sandy site. *Restor. Ecol.* **2019**, *27*, 289–297. [CrossRef]
35. Lan, S.; Wu, L.; Zhang, D.; Hu, C. Successional stages of biological soil crusts and their microstructure variability in Shapotou region (China). *Environ. Earth Sci.* **2012**, *65*, 77–88. [CrossRef]
36. Li, J.; Li, J.; Duan, X.; Zhang, X.; Liu, J. Functional genomic analysis of nutrient cycling of plant-soil continuum in the mossy biocrust in the Tengger Desert. *Rhizosphere* **2023**, *28*, 100806. [CrossRef]
37. Qi, J.; Liu, Y.; Wang, Z.; Zhao, L.; Zhang, W.; Wang, Y.; Li, X. Variations in microbial functional potential associated with phosphorus and sulfur cycling in biological soil crusts of different ages at the Tengger Desert, China. *Appl. Soil Ecol.* **2021**, *165*, 104022. [CrossRef]
38. Kidron, G.J.; Veste, M.; Lichner, L.U. Biological factors impacting hydrological processes: Pecularities of plants and biological soil crusts. *J. Hydrol. Hydromech.* **2021**, *69*, 357–359. [CrossRef]
39. Muller, K.; Veste, M.; Privett, S.; Strauss, P.; Makunga, N.; Griebenow, S.; Valentine, A. *Proteaceae* species show different strategies for phosphorus acquisition and utilisation in p poor soils in the mediterranean-type fynbos ecosystem. *Flora* **2023**, *306*, 152362. [CrossRef]
40. Veste, M.; Felde, V.J.M.N.L.; Warren, S.D.; Pietrasiak, N. Editorial: Ecological development and functioning of biological soil crusts after natural and human disturbances. *Front. Ecol. Evol.* **2021**, *9*, 713584. [CrossRef]
41. Fan, J.; Li, S.; Yu, H.; Huang, J.J. Soil enzyme activity and carbon, nitrogen and phosphorus stoichiometric characteristics under different types of biocrusts and subsoil in mu us Sandland. *J. Desert Res.* **2021**, *41*, 109.
42. Helming, K.; Luis Rubio, J.; Boardman, J. Soil erosion across Europe: Research approaches and perspectives. *Catena* **2006**, *68*, 71–72. [CrossRef]
43. Dan, C.; Liu, G.; Zhang, Q.; Zhao, Y.; Shen, E.; Liu, C.; Shu, C.; Liu, Y.; Xia, X.; Liu, D.; et al. Predicting the coupling effects of grass and shrub with biological crust on splash and sheet erosion. *Soil Tillage Res.* **2024**, *244*, 106208. [CrossRef]
44. Aranibar, J.N.; Repetur, M.J.; Garcia, V.R.; Dazat, R.E.; Videla, M.E.C.; Villagra, P.E. Functional responses of biological soil crusts to simulated small precipitation pulses in the monte desert, Argentina. *Geoderma* **2022**, *410*, 115660. [CrossRef]
45. Li, X.; Zheng, J.; Li, X.; Tan, H.; Pan, Y.; Wei, Y. Responses of runoff, sedimentation, and induced nutrient loss to vegetation change in the Tengger Desert, northern China. *Soil Res.* **2013**, *51*, 124–132. [CrossRef]
46. Condon, L.A.; Pietrasiak, N.; Rosentreter, R.; Pyke, D.A. Passive restoration of vegetation and biological soil crusts following 80 years of exclusion from grazing across the great basin. *Restor. Ecol.* **2020**, *28*, S75–S85. [CrossRef]
47. Liu, Y.-F.; Liu, Y.; Wu, G.-L.; Shi, Z.-H. Runoff maintenance and sediment reduction of different grasslands based on simulated rainfall experiments. *J. Hydrol.* **2019**, *572*, 329–335. [CrossRef]
48. Gomez, D.A.; Aranibar, J.N.; Tabeni, S.; Villagra, P.E.; Garibotti, I.A.; Atencio, A. Biological soil crust recovery after long-term grazing exclusion in the monte desert (Argentina). Changes in coverage, spatial distribution, and soil nitrogen. *Acta Oecol.-Int. J. Ecol.* **2012**, *38*, 33–40. [CrossRef]
49. Moreira-Grez, B.; Tam, K.; Cross, A.T.; Yong, J.W.H.; Kumaresan, D.; Nevill, P.; Farrell, M.; Whiteley, A.S. The bacterial microbiome associated with arid biocrusts and the biogeochemical influence of biocrusts upon the underlying soil. *Front. Microbiol.* **2019**, *10*, 2143. [CrossRef]
50. Tian, C.; Xi, J.; Ju, M.; Li, Y.; Guo, Q.; Yao, L.; Wang, C.; Lin, Y.; Li, Q.; Williams, W.J.; et al. Biocrust microbiomes influence ecosystem structure and function in the Mu Us Sandland, northwest China. *Ecol. Inform.* **2021**, *66*, 101441. [CrossRef]
51. Bowker, M.A.; Rengifo-Faiffer, M.C.; Antoninka, A.J.; Grover, H.S.; Coe, K.K.; Fisher, K.; Mishler, B.D.; Oliver, M.; Stark, L.R. Community composition influences ecosystem resistance and production more than species richness or intraspecific diversity. *Oikos* **2021**, *130*, 1399–1410. [CrossRef]
52. Lan, S.; Wu, L.; Zhang, D.; Hu, C. Assessing level of development and successional stages in biological soil crusts with biological indicators. *Microb. Ecol.* **2013**, *66*, 394–403. [CrossRef] [PubMed]
53. Mai, Z.; Chen, Q.; Wang, L.; Zhang, J.; Cheng, H.; Su, H.; Zhang, S.; Li, J. Bacterial carbonic anhydrase-induced carbonates mitigate soil erosion in biological soil crusts. *J. Environ. Manag.* **2024**, *352*, 120085. [CrossRef]
54. Wu, Y.; Rao, B.; Wu, P.; Liu, Y.; Li, G.; Li, D. Development of artificially induced biological soil crusts in fields and their effects on top soil. *Plant Soil* **2013**, *370*, 115–124. [CrossRef]
55. Chowaniec, K.; Styburski, J.; Koziol, S.; Pisanska, Z.; Skubala, K. Dune blowouts as microbial hotspots and the changes of overall microbial activity and photosynthetic biomass along with succession of biological soil crusts. *Microb. Ecol.* **2024**, *87*, 22. [CrossRef]
56. Steggles, E.K.; Facelli, J.M.; Ainsley, P.J.; Pound, L.M. Biological soil crust and vascular plant interactions in western myall (*Acacia papyrocarpa*) open woodland in south Australia. *J. Veg. Sci.* **2019**, *30*, 756–764. [CrossRef]


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