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Microbial Fertilizers and Shading Contribute to the Vegetation Assembly and Restoration of Steep-Slope after Soil Spray-Sowing in the Yuanjiang Dry-Hot Valley Region

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Abstract: Road construction and strip mining in mountainous regions inevitably causes the destruction of vegetation and soil, leading to large ranges of exposed slopes. Although soil spray-sowing has become a promising method to accelerate community assembly in humid regions, the application of microbial fertilizers and shading in slope recovery during soil spray-sowing are rarely reported in dry-hot valleys. This study compared the effectiveness among artificial seeding, arch column + planting bags, and soil spray-sowing by slope restoration trials in the Yuanjiang dry-hot valley, southwest China. Additionally, we explored the effect of slope degrees, shade, and microbial fertilizers on seedling survival and growth after soil spray-sowing. Results indicated that soil spray-sowing displayed better species survival and growth performance than artificial seeding and arch column + planting bags. The richness, density, and height of seedlings dropped dramatically with the increasing of slope degrees after soil spray-sowing, especially when the slope degree was greater than 1. Although shading observably improved the species density, it inhibited the growth of *Albizia julibrissin* and *Crotalaria pallida*. Moreover, microbial fertilizers *Penicillium chrysogenum* and *Bacillus aryabhattai* markedly enhanced the density and growth of species *Azadirachta Indica*, *Cajanus cajan*, *Indigofera cassioides*, and *Sophora xanthanth*. Soil spray-sowing, combined with shading and microbial fertilizers, contributes to species survival and growth when the slope degree is less than 1.73 and the soil spray-sowing process coincides with the rainy season, which provides the theoretical basis and technical support for ecological restoration in the dry-hot river valley.

Keywords: dry-hot valley; microbial community; slope gradient; arid and semi-arid areas; vegetation restoration; soil spray-sowing

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1. Introduction

The construction of roads, reservoirs and strip mining inevitably results in the destruction of soil structures and surface vegetation [1,2], ultimately leading to large ranges of exposed slopes [3,4], especially in arid and semi-arid mountain areas in southwest China with shallow soil, intense radiation, low rainfall and heavy surface runoff [5]. The restoration of exposed slopes can not only lessen landslides and traffic accidents [6], but can improve the aesthetics and accelerate the rural revitalization that tends to incorporate the development of tourist attractions [7,8].

Traditional restoration methods of high-steep slopes along roads, rivers, and lakes usually combines protection with afforestation via protective screening, natural restoration, aerial seeding, arch column + seeds, and arch column + planting bags [9–11]. Studies have shown that the application of protective nets can prevent gravel from falling in rocky landscapes, but significantly detract from the beauty of the landscape for tourists and motorists [12]. Kardiman et al. [13] stated that natural restoration is the least costly mean for the recovery of gentle slope in humid areas, but the practice quickly becomes dominated by herbaceous plants and invasive species because of lack of soil seed banks in sites experiencing severe degradation [14–16]. Arch column + seeds and arch column + planting bags have been widely used in slope repair along expressways and high-speed railway, with small-scale benefits seen throughout the country [17,18], but most results have indicated that they were not only costly and aesthetically unpleasant, but arch columns also impeded the horizontal movement of plant roots and soil water, ultimately resulting in regional drought and seedling death [19–21].

Current restoration methods take into account not only species maintenance and diversity, but the community structure of trees-shrubs-herbs and the interactions between soil, root, and microorganism [22,23]. Zhao et al. [24] concluded that topsoil translocation was conducive to the restoration of karst rocky deserts in southwest China, and moderate shade enhanced the survival of woody seedlings and the similarity between new communities and donor forest communities. In particular, soil spray-sowing showed promise as an effective mean for steep-slopes recovery, achieving remarkable effects in wet and sub-humid regions [25,26] (Li et al. 2017; Fu et al. 2018), ultimately forming plant communities combining flowers, shrubs, and grass [27] (Wang et al. 2021). Additionally, studies have confirmed that microbial fertilizers had been widely used in agriculture and increased the output and quality of agricultural products [28,29]. However, there are no reports on the application of soil spray-sowing technology for slope restoration in the dry-hot valleys area, and there is a lack of research on the effects of microbial fertilizers and shade on seedling establishment during soil spray-sowing.

The study selected native dominant species and microbial fertilizers for slope restoration trials in the Yuanjiang dry-hot valley. It aimed (1) to compare the differences among artificial seeding, arch column + planting bags, and soil spray-sowing in the Yuanjiang dry-hot valley; (2) to explore the effects of microbial fertilizers and shading treatment on seedling survival and growth after soil spray-sowing; (3) analyze the restoration benefit among different slope degrees, which answer the following two questions: (1) what methods and treatments are most appropriate for slope restoration in dry-hot valleys? and (2) what are the survival and adaptation mechanisms of different species?

2. Materials and Methods

2.1. Study Site

The study site is located in Honghe County (N 23°05′–N 23°27′, E 102°49′–E 103°37′), Yunnan Province, Southwest China, belonging to one of the most fragile and typical dry-hot valleys [30]. Mountainous land covers 96% of the county, with elevations ranging from 259 m to 2745 m, and the dry-hot valley area primarily occurs at altitudes below 1200 m. The mean annual precipitation is 680–780 mm, most of it (about 85%) falling in the rainy season (May to October), and mean annual evaporation capacity (about 2500 mm) is considerably greater than the precipitation in the dry-hot valley area [31,32]. The area features Latosol and Ferralsol soil types [33], which demonstrate poor nutrition and poor water retention [34].

The restoration of dry-hot valley regions is difficult [30], especially when the vegetation community and soil structures are destroyed and turned into steep slopes during the construction of roads, reservoirs, and mining [27,35,36]. Therefore, the selection of plant species and restoration methods is a critical step for slope restoration, and we selected 12 native dominant species (two trees (*Albizia julibrissin* [Leguminosae] and *Azadirachta Indica* [Meliaceae]), four shrubs (*Cajanus cajan* [Leguminosae], *Crotalaria pallida* [Leguminosae], *Indigofera cassioides* [Leguminosae] and *Sophora xanthanth* [Leguminosae]), and six herbs (*Atylosia scarabacoides* [Leguminosae], *Melinis minutiflora* [Gramineae], *Eragrostis pilosa*

[Gramineae], *Cosmos bipinnata* [Compositae], *Cynodon dactylon* [Gramineae], and *Celosia argentea* [Amaranthaceae]) as experimental materials to probe their adaptability in slope restoration. Moreover, plant seeds were collected by our team from Yuanjiang's dry-hot valley and added to the experiment at a rate of 4 g/m^2 for each species, and the total weight of seeds was 48 g for 1 m^2.

2.2. Comparative Study on Slope Restoration Methods among Artificial Seeding, Arch Columns + Planting Bags, and Soil Spray-Sowing

We conducted an artificial seeding (AS), arch columns + planting bags (AC + PB), and soil spray-sowing (SSS) experiment on slope degrees of 1 in August 2020 near the Red River Valley toll station of the Yuanjiang-Manhao expressway to compare the effects among them. Artificial seeding was done by uniformly sowing mixed seeds, and the total weight of seeds was 48 g/m^2 on the soft slope surface (10 cm). The arch columns were finished by a building worker, and we finished planting bags by mixing surface soil and seeds (48 g/m^2), bagging and stacking planting bags among arch columns. The depth of planting bags was 10 cm (Figure 1).

Figure 1. The schematic diagram and effect of artificial seeding, arch columns + planting bags, and soil spray-sowing.

More importantly, soil spray-sowing had physical protection, corrosion resistance protection, and vegetation protection [25,27]. First, a 40 cm anchor rod was used to affix the physical protection, 5 cm × 5 cm galvanized metal mesh, to the slope surface. Second, the anti-corrosion protection (2–3 cm) comprising biological binder material + coagulator + soil was added using soil spray-sowing technology. Third, the vegetation protection was also added using soil spray-sowing technology; it was divided into water-retaining-agent layer (3–5 cm) and seed layer (2–3 cm) (Figure 2). Each restoration method layout had 10 samples, and each sample set 20 m^2 and a total of 200 m^2 for the field experiment on slope degrees of 1 (corresponding slopes angles of 45°).

Figure 2. The process diagram of the soil spray-sowing technique, including the hanging net (**A**), soil spray-sowing (**B**), experiment treatments, and labeling (**C**).

2.3. Effect of Slope Degrees on Seedling Survival and Growth during Soil Spray-Sowing

To explore the effect of slope degrees on seedling survival and growth, soil spray-sowing experiments were carried out on slope degrees of 0.27, 0.58, 1.00, 1.73, and 3.73, and corresponding slope angles were approximately 15°, 30°, 45°, 60°, and 75° respectively. Each slope degree set 10 samples, and each sample was 20 m^2 and a total of 200 m^2 for each slope degree.

2.4. Effect of Shade Treatment on Seedling Survival and Growth after Soil Spray-Sowing

To verify the effects of shade on seedlings' survival and growth, shade conditions (shade degree is about 50%) were created by using a shading net after soil spray-sowing on slope degrees of 1 (corresponding slopes angles is 45°), with no-shade as a blank control. The shade and no-shade set 10 samples respectively, and each sample arranged 20 m^2 and total 200 m^2 for the restoration trial.

2.5. Effects of Microbial Fertilizers on Seedling Survival and Growth after Soil Spray-Sowing

To seek the best microbial fertilizers for slope restoration, four kinds of microbial fertilizers (A (*Penicillium chrysogenum*), B (*Serratia marcescens*), C (*Kocuria rosea*), and D (*Bacillus aryabhattai*)) were added to seed layers respectively during soil spray-sowing on slope degrees of 1 (the corresponding slope angle was 45°). The amount of microbial fertilizer was 50 mL/m^2, according to instructions, and the same proportion of water was added as a blank control (CK). Four kinds of microbial fertilizer were described as A, B, C, and D, standing for *Penicillium chrysogenum*, *Serratia marcescens*, *Kocuria rosea*, and *Bacillus aryabhattai*, respectively, which were isolated, extracted, identified by Kunming Institute of Botany, Chinese Academy of Sciences, and cultivated by Nanning Han-He Biological Technology Co., LTD. (Nanning, China). Each microbial fertilizer set 10 samples, and each sample carried out 20 m^2 and a total of 200 m^2 for each microbial fertilizer.

One year after soil spray-sowing, one quadrat (1 m × 1 m) in each sample was established to record the number of species (species richness), and the abundance of each species (seedling density) in different restoration methods, slope degrees, shade treatments, and microbial fertilizers, and each treatment set 10 repetitions. Moreover, the ground diameter (basal diameter) and the height of each woody species (tree species + shrub species) in different restoration methods, slope degrees, shade treatments, and microbial fertilizers were measured with a vernier caliper and a ruler, respectively.

2.6. Statistical Analysis

All analyses were conducted in the R 3.5 version, and the ANOVA and Tukey HSD functions were used to compare species richness and density among artificial seeding, arch columns + planting bags, and soil spray-sowing, as well as different slope degrees, shade, and microbial fertilizers. Moreover, the ground diameter and height of woody species at different restoration methods, slope degrees, shade, and microbial fertilizers were also analyzed by ANOVA and Tukey HSD functions. Additionally, normal distribution and homogeneity of variances were examined by the Shapiro-Wilk test and Levene's test [37].

3. Results

3.1. The Difference among Artificial Seeding, Arch Columns + Planting Bags, and Soil Spray-Sowing

The richness and density of seedlings in artificial seeding (AS) reached only six species (one tree, two shrubs, and three herbs) and 8.0 seedlings/m^2, respectively; significantly lower than that of arch columns + planting bags (AC + PB), and soil spray-sowing (SSS) ($p < 0.05$). Moreover, although 10 out of 12 species (two trees, three shrubs, and five herbs) survived from AC + PB, the density was only 17.0 seedlings/m^2, which was significantly inferior to SSS, whose species richness and density reached 12 species and 29.9 seedlings/m^2, respectively ($p < 0.01$) (Figure 3).

Not all woody species germinated or survived after 1 year, except for the soil spray-sowing method, and *A. Indica*, *I. cassioides*, and *S. xanthanth* were not discovered in AS and *S. xanthanth* in AC + PB. The ground diameter and height of *A. julibrissin* were greater in the order of AS > AC + PB > SSS ($p < 0.05$). On the contrary, the ground diameter and height of *C. cajan* and *C. pallida* displayed AS < AC + PB < SSS. In particular, the height of *C. cajan* and *C. pallida* reached 62.3 cm and 60.4 cm, respectively, after soil spray-sowing (Table 1).

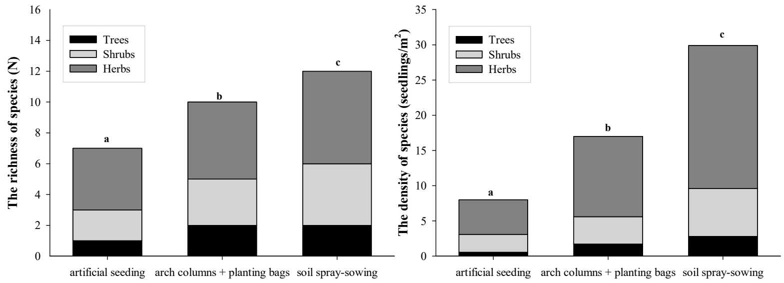

Figure 3. The richness and density of artificial seeding (AS), arch columns + planting bags (AC + PB), and soil spray-sowing (SSS). Different lowercase letters in the same index means the difference varies significantly among different methods.

Table 1. Ground diameter and height of woody species among artificial seeding (AS), arch columns + planting bags (AC + PB), and soil spray-sowing (SSS) ("—" stands for missing data, and different lowercase letters in the same index means the difference varies significantly among different methods).

Index	Ground Diameter (mm)			Height (cm)		
Species Name	**AS**	**AC + PB**	**SSS**	**AS**	**AC + PB**	**SSS**
Albizia julibrissin	6.5 ± 1.1 a	5.2 ± 1.0 b	3.1 ± 0.3 c	50.5 ± 3.1 a	65.4 ± 4.5 b	35.8 ± 2.3 c
Azadirachta Indica	—	4.5 ± 0.7 a	5.7 ± 1.2 b	—	45.5 ± 2.0 a	32.4 ± 2.6 b
Cajanus cajan	4.4 ± 0.6 a	5.1 ± 0.9 a	6.6 ± 2.1 b	35.6 ± 3.2 a	47.6 ± 4.3 b	62.3 ± 4.2 c
Crotalaria pallida	2.2 ± 1.0 a	2.3 ± 0.5 a	3.4 ± 0.6 b	27.5 ± 2.1 a	34.6 ± 4.6 b	60.4 ± 4.9 c
Indigofera cassioides	—	3.3 ± 0.4 a	1.1 ± 0.2 b	—	25.5 ± 3.4 a	38.6 ± 3.5 b
Sophora xanthanth	—	—	4.8 ± 0.5	—	—	27.5 ± 5.3

3.2. The Effect of Slope Degrees on Seedling Survival and Growth after Soil Spray-Sowing

Species richness and density decreased as slope degree increased, regardless of tree, shrub, or herb species. Although 12 species survived when the slope degree was lower than and equal to 1, the density gradually trended downward with the increase of the slope degree. In particular, the richness and density number declined sharply when the slope degree was greater than 1 ($p < 0.05$). The species richness and density reached 12 species and 40.4 seedlings/m^2, respectively, when the slope degree was 0.27, but only seven species and 6.3 seedlings/m^2 when the slope degree was 2.73 ($p < 0.01$) (Figure 4).

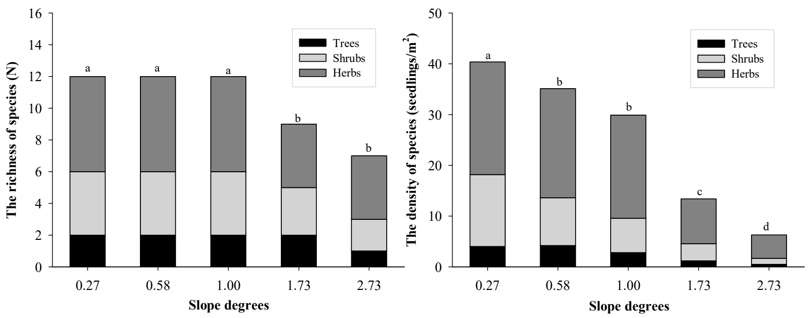

Figure 4. The species richness and density of different life forms in different slope degrees. Different lowercase letters in the same index means the difference varies significantly among different methods.

A Indica, *I. cassioides*, and *S. xanthanth* were not recorded when the slope degree was 2.73. The ground diameter and height of *A. julibrissin* decreased significantly when the slope degree was greater than 1, and there was no significant difference between 1.73 and 2.73. For *C. cajan* and *C. pallida*, the ground diameter and height clearly dropped as slope degree increased, but there was no significant difference between 1.73 and 2.73. Moreover, the slope degree did not impact the ground diameter of *A. Indica* and *S. xanthanth*, but decreased the height significantly (Table 2).

Table 2. The ground diameter and height of each woody plant among slope degrees ("—"stands for missing data, and different lowercase letter in the same index means the difference varies significantly among different slope degrees).

Slope Degree	Ground Diameter (mm)					Height (cm)				
Species	0.27	0.58	1.00	1.73	2.73	0.27	0.58	1.00	1.73	2.73
A. julibrissin	5.6 ± 1.1 a	5.5 ± 0.5 a	3.1 ± 0.3 b	2.6 ± 0.3 c	2.7 ± 0.5 c	61.6 ± 6.2 a	55.5 ± 3.5 a	35.8 ± 2.3 b	23.7 ± 3.3 c	20.8 ± 1.6 c
A. Indica	6.5 ± 1.2 a	6.2 ± 0.4 a	5.7 ± 1.2 a	4.9 ± 0.5 a	—	66.5 ± 7.2 a	48.2 ± 3.4 b	32.4 ± 2.6 c	27.3 ± 3.5 c	—
C. cajan	8.4 ± 1.3 a	7.5 ± 2.1 b	6.6 ± 2.1 c	3.5 ± 0.5 d	3.1 ± 0.7 d	85.4 ± 8.3 a	74.5 ± 2.7 b	62.3 ± 4.2 c	43.3 ± 2.7 d	39.3 ± 4.3 d
C. pallida	7.2 ± 0.8 a	4.6 ± 0.7 b	3.4 ± 0.6 c	3.2 ± 0.6 c	2.6 ± 0.2 c	77.2 ± 7.8 a	74.5 ± 5.7 a	60.4 ± 4.9 b	33.4 ± 5.2 c	32.6 ± 6.6 c
I. cassioides	2.5 ± 0.4 a	1.3 ± 0.2 b	1.1 ± 0.2 b	1.0 ± 0.1 b	—	52.5 ± 6.3 a	41.3 ± 5.4 a	38.6 ± 3.5 b	20.3 ± 3.6 c	—
S. xanthanth	5.5 ± 1.1 a	5.2 ± 0.5 a	4.8 ± 0.5 a	—	—	55.3 ± 4.1 a	47.4 ± 3.5 a	27.5 ± 5.3 b	—	—

3.3. The Effect of Shade on Seedling Survival and Growth after Soil Spray-Sowing

Shading did not affect species richness, but significantly improved the density of seedlings. The density of tree, shrub, and herb species were only 2.8, 6.8, and 20.3 seedlings/m^2 without shade, but they reached 4.5, 12.8, and 29.4 seedlings/m^2, respectively, when shade was given after soil spray-sowing (p < 0.05) (Figure 5).

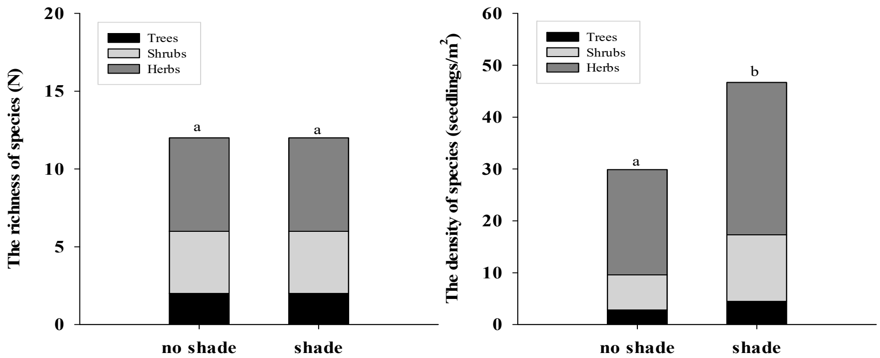

Figure 5. The effect of shade on species richness and density of different life forms. Different lowercase letters in the same index means the difference varies significantly among different methods.

Shade enhanced the density of woody species, but it inhibited the height of *A. julibrissin* and *C. pallida*. Moreover, shade also significantly improved the ground diameters and heights of *A. Indica*, *I. cassioides* and *S. xanthanth* by 48.8%, 32.9%, and 54.2%, respectively (p < 0.05). In particular, *C. cajan* grew well in both shady and non-shady conditions, and the heights reached 62.3 cm and 64.5 cm, respectively (Table 3).

Table 3. The effect of shade on the ground diameter and height of woody species (different lowercase letter in same index means the difference varies significantly between shade and no shade).

Treatments	Ground Diameter (mm)		Height (cm)	
Species	No Shade	Shade	No Shade	Shade
A. julibrissin	3.1 ± 0.3 a	2.8 ± 0.4 a	35.8 ± 2.3 a	27.3 ± 2.4 b
A. Indica	5.7 ± 1.2 a	6.3 ± 0.6 b	32.4 ± 2.6 a	48.2 ± 3.4 b
C. cajan	6.6 ± 2.1 a	6.5 ± 2.1 a	62.3 ± 4.2 a	64.6 ± 5.7 a
C. pallida	3.4 ± 0.6 a	2.9 ± 0.2 a	60.4 ± 4.9 a	74.5 ± 5.7 b
I. cassioides	1.1 ± 0.2 b	2.5 ± 0.3 b	38.6 ± 3.5 a	51.3 ± 4.3 b
S. xanthanth	4.8 ± 0.5 a	6.5 ± 1.1 a	27.5 ± 5.3 a	42.4 ± 4.5 b

3.4. The Effect of Microbial Fertilizers on Seedling Survival and Growth after Soil Spray-Sowing

Microbial fertilizers obviously promoted the density of shrub and herb species, especially for *P. chrysogenum*, *S. marcescens*, and *B. aryabhattai*, and the density of seedlings reached 43.7, 51.1, and 59.7 seedlings/m^2, respectively ($p < 0.05$), but the density was only 29.9 seedlings/m^2 without adding microbial fertilizers (Figure 6).

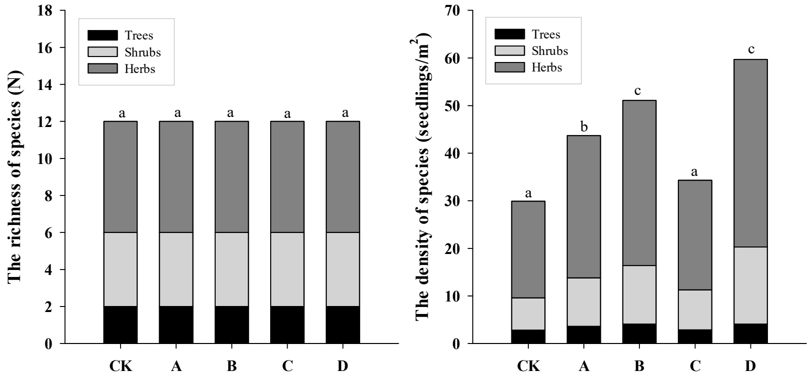

Figure 6. The effect of microbial fertilizers A (*Penicillium chrysogenum*), B (*Serratia marcescens*), C (*Kocuria rosea*) and D (*Bacillus aryabhattai*) on species richness and density. Different lowercase letters in the same index means the difference varies significantly among different methods.

The effect of microbial fertilizers A, B, C, and D on the ground diameter of woody species *A. Indica*, *C. cajan*, *C. pallida*, *I. cassioides*, and *S. xanthanth* were not significantly different, but they markedly promoted the height of species *A. Indica*, *C. cajan*, *C. pallida*, *I. cassioides*, and *S. xanthanth*. Moreover, microbial fertilizers A and D dramatically improved the ground diameter and height of *A. julibrissin* (Table 4).

Table 4. The ground diameter and height of woody species in microbial fertilizers A (*Penicillium chrysogenum*), B (*Serratia marcescens*), C (*Bacillus aryabhattai*), D (*Bacillus aryabhattai*), and CK (without microbial fertilizer) (different lowercase letter in same index indicates significant difference among microbial fertilizers).

Treatments	Ground Diameter (mm)					Height (cm)				
Species	CK	A	B	C	D	CK	A	B	C	D
A. julibrissin	3.1 ± 0.3 a	4.4 ± 0.3 b	5.0 ± 1.1 b	2.9 ± 0.4 a	4.3 ± 0.6 b	35.8 ± 2.3 a	45.3 ± 6.2 b	37.6 ± 2.4 a	33.5 ± 2.4 a	46.7 ± 5.6 b
A. Indica	5.7 ± 1.2 a	6.1 ± 1.1 a	5.9 ± 1.3 a	6.2 ± 1.0 a	5.6 ± 0.6 a	32.4 ± 2.6 a	48.2 ± 3.4 b	44.4 ± 3.2 b	29.6 ± 3.1 a	58.2 ± 5.3 c
C. cajan	6.6 ± 2.1 a	6.6 ± 2.7 a	6.7 ± 1.0 a	6.8 ± 0.7 a	7.1 ± 1.1 a	62.3 ± 4.2 a	75.3 ± 6.3 b	72.4 ± 3.2 b	69.4 ± 4.2 b	82.4 ± 7.2 c
C. pallida	3.4 ± 0.6 a	3.6 ± 0.3 a	3.4 ± 1.0 a	3.2 ± 0.2 a	3.7 ± 0.4 a	60.4 ± 4.9 a	69.6 ± 4.5 b	71.2 ± 5.2 b	62.2 ± 4.3 a	72.1 ± 3.8 b
I. cassioides	1.1 ± 0.2 a	1.8 ± 0.2 a	2.3 ± 0.3 a	1.4 ± 0.2 a	1.8 ± 0.5 a	38.6 ± 3.5 a	50.6 ± 6.2 b	53.7 ± 2.7 b	42.2 ± 4.1 a	55.4 ± 7.2 b
S. xanthanth	4.8 ± 0.5 a	5.3 ± 1.2 a	4.7 ± 0.3 a	5.2 ± 0.3 a	5.4 ± 1.0 a	27.5 ± 5.3 a	38.2 ± 4.1 b	45.5 ± 7.2 c	39.3 ± 2.2 b	48.1 ± 8.0 c

4. Discussion

4.1. The Application of Soil Spray-Sowing in Vegetation Restoration

The restoration of severely degraded areas and the improvement of low-efficiency forests are the most important elements in increasing forest coverage rates [38]. The restoration of dry-hot valley regions is difficult [30], especially for steep slopes, as a result of the construction of roads, reservoirs, and mining [27,35,36]. Our results indicate that soil spray-seeding not only improves species richness and abundance, but also accelerates seedling growth when compared with artificial seeding and arch columns + planting bags in the Yuanjiang dry-hot valley region, which aligns with studies suggesting that soil spray-seeding is the superior method for vegetation restoration of expressway slopes in semi-humid areas [25,26], and that soil spray-seeding provides a good soil substrate for plant growth and community assembly combining shrubs, flowers, and grass [39–41]. Shang et al. [42] indicated that natural recovery is a simple and cheap way to increase grass coverage in sub-humid and humid areas, but that was unsuccessful for slope recovery in the dry-hot valley region, probably because (1) seeds on soil surfaces are more vulnerable to animal feeding and sun exposure; (2) steep slopes tend to cause seed loss and soil erosion during the rainy season; (3) climate conditions in the dry-hot valley inhibited the germination and growth of many species; (4) the degraded land lacked seed banks for woody tree species [43–45]. Although arch columns + planting bags have produced good results for the restoration of slopes along highways and railway in certain areas [46], they are expensive and unsuitable in the dry-hot valley area. This is mainly because partitioned arch columns impede the horizontal movement of plant roots and soil water, and the gaps among planting bags accelerate the evaporation of soil water [47], ultimately leading to regional droughts and species failure [18], potentially owing to seeds being planted too deep to germinate in planting bags.

4.2. The Effect of Environmental Conditions and Soil Microorganisms on Seedling Survival and Growth after Soil Spray-Sowing

The environmental assembly model considered that communities are structured primarily by species' physiological and demographic responses to the physical environment [48,49]. It is predicated on all species having finite environmental requirements or tolerances, especially regarding soil conditions, light, and water, which affects community membership [50]. Our study suggested that soil spray-sowing was the best method for the vegetation of steep slopes in the Yuanjiang dry-hot valley region, but species survival and growth declined sharply with the increase in slope degree, especially when the slope degree exceeded 1.73, which was consistent with previous studies showing that soil spraying + hanging nets exerted a significant effect on the ecological protection of gently sloping stone regions in wetland areas, ultimately forming a plant community with a trees-shrubs-herbs combination [41,51,52]. Other methods, such as topsoil translocation, can also promote vegetation coverage of degradation sites and accelerate the establishment of the seedlings community toward forests. This is because forest topsoil contains all kinds of seed banks and soil microorganisms, but it is only suitable for gentle slopes in sub-humid regions [24,53,54].

The effect of light on seed germination is mainly as a signal stimulus to interrupt seed dormancy, rather than as a source of energy directly involved in the seed germination process [24,55]. Our study indicated that shading significantly improved the species density of trees, shrubs, and herbs, but inhibited the growth of *A. julibrissin* and *C. pallida* after soil spray-sowing, which was similar to a study suggesting that long-term shading can impact the growth and regeneration of *A. julibrissin*, *C. pallida* and other herbaceous plants [56]. Another study also indicated that moderate to heavy shade (37.5%–70% shade) improved the diversity and density of woody species in the seedling stage during topsoil translocation but restrained the density of herb and liana species while hindering the regeneration and growth of heliophilous species, such as *Rhus chinensis*, *Ligustrum lucidum* or *Broussonetia papyrifera* [24]. Moreover, studies concluded that moderate shade is not altering environmental conditions, mainly due to the increased light heterogeneity [57–59] and facilitating the occurrence of diverse microsite patches for seed germination and seedling regeneration [60–62]. On the contrary, some researchers have suggested that forest gaps provided a favorable environment for maintaining gap-phase regeneration dynamics in forest ecosystems [63].

Soil microorganisms are important components of soil community and play a key role in soil biochemical processes, including organic matter degradation, nutrient mineralization, and recycling [29]. Our results highlighted that microbial fertilizers significantly increased the density and growth of woody species, especially for the microbial fertilizers *Penicillium chrysogenum* and *Bacillus aryabhattai*, which accelerated the height growth of *A. indica*, *C. cajan*, *I. cassioides*, and *S. xanthantha*. We also detected many root nodules in the roots of legumes, consistent with a past study indicating that microbial agents or fertilizers produced by active soil microorganisms have been widely used in agricultural production, mountain greening, and ecological restoration with positive benefits [64], and that microbial fertilizers contribute to plant survival and growth by promoting the formation of root nodules in legumes [65]. Moreover, studies have shown that symbiosis of plant and microorganisms can impact the survival and adaptability of plants, especially for plants in desert and semi-desert regions [13]. One study has even shown that arbuscular mycorrhizal fungi negatively affect soil seed bank viability [66].

5. Conclusions

The selection of species and methods is critical for vegetation reconstruction and restoration of steep-slopes resulting from the construction of highways, roads, reservoirs, and mining. This study indicates that soil spray-sowing is an effective method for slope restoration in the Yuanjiang dry-hot valley when the slope degree is less than or equal to 1.73, and that the application of shading net and microbial fertilizers (*Penicillium chrysogenum* and *Bacillus aryabhattai*) can further improve the survival and growth performance of woody species at the seedling stage if soil spray-sowing coincides with the rainy season. These findings can be used to help prevent geological disasters and provide a theoretical basis and technical support for the ecological restoration of similar degraded sites.

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