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Effect of Geographical Conditions on Moss–Soil Crust Restoration on Cut Rock Slopes in a Mountainous Area in Western Sichuan, China

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Abstract: Ecological restoration has great significance on cut rock slopes, which are considered extremely degraded habitats. The development of moss–soil crusts on cut rock slopes as a critical pathway to ecological restoration in mountain areas has been poorly reported. A total of 335 quadrats were selected on cut rock slopes with formation ages between 0 and 60 years to evaluate the evolution characteristics of moss–soil crusts under various geographical conditions (e.g., aspect, lithology, and altitude) in the mountainous area of western Sichuan, Southwest China. The results suggested that moss growth decoupled from soil accumulation within the crusts and was controlled by multiple factors. Moss growth depended on lithology, altitude, and age, while soil weight was mainly influenced by slope aspect. The development of mosses on limestone was better than on sandstone. Moss biomass varied with altitude, consistent with that of rainfall with respect to moss development dependent on moisture. Furthermore, moss development under a semiarid climate was more distinctly impacted by moisture with altitude relative to a humid region, likely owing to the higher sensitivity of the mosses to moisture in the former than in the latter. Moss biomass increased with recovery time, while the rate of moss biomass development was diverse in different geographical areas. The vegetation developed rapidly in low-altitude areas (~1000 m above sea level), resulting in moss biomass increasing from 0 to 24.08 $g \cdot m^{-2}$ with formation time increasing from 0.5 to 1.5 years and subsequently being restricted by the evolution of higher plants on cut rock slopes, leading to an insignificant difference in moss biomass between 1.5 and 60 years. In high-altitude areas, when the altitude changed slightly (from 2024 to 2430 m above sea level), the moss biomass on cut rock slopes increased linearly with increasing age from 5 to 27 years. Influenced by the surrounding fertile soils and moss bioaccumulation, there were high levels of soil major nutrient content, especially the organic matter content, which reached 377.42 $g \cdot kg^{-1}$. More soils accumulated on south-facing slopes than on north-facing slopes. This study provided field data to clearly reveal the influence of geographic factors on moss–soil crust development in natural restoration processes in high-altitude mountainous areas.

Keywords: cut rock slope; natural recovery; moss–soil crust; biomass; soil accumulation; mountainous area

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Citation: Pu, W.; Zhao, M.; Du, J.; Liu, Y.; Huang, C. Effect of Geographical Conditions on Moss–Soil Crust Restoration on Cut Rock Slopes in a Mountainous Area in Western Sichuan, China. *Sustainability* **2023**, *15*, 1990. https://doi.org/10.3390/su15031990

Academic Editor: Teodor Rusu

Received: 15 December 2022
Revised: 4 January 2023
Accepted: 18 January 2023
Published: 20 January 2023

1. Introduction

A large number of steep rocky slopes have been formed due to the construction of roads (e.g., railways and highways), dams, and mining facilities [1]. On the high and steep cut rock slopes, the vegetation–soil system was partially or completely destroyed, and as a resultant, abominable habitats were produced [1–3].

To rehabilitate areas suffering degradation, technologies such as hydroseeding, external soil spray seeding, and erosion control blankets have been widely used [4]. However, most of these technologies were manually recovered using geotechnical techniques, and less consideration was given to natural recovery [5]. Natural restoration was more important in mountainous areas with inconvenient traffic conditions, given the high cost and technical content, large quantities required, potential for secondary damage, and other problems of manual restoration [6,7]. It has been claimed that natural restoration could be more efficient than human efforts in restoring degraded land and vegetation conditions [8,9].

Recently, the natural restoration of cut rock slopes has received increasing attention. Numerous studies have demonstrated soil nutrient accumulation and vegetation community succession following the implementation of ecological restoration programs on cut rock slopes [2,10,11]. Meanwhile, the influence of environmental factors, such as aspect, gradient, and time, on the natural restoration of slope vegetation was discussed. For example, soil properties, e.g., the moisture and organic matter contents of soils on north-facing slopes, are significantly higher than those on south-facing slopes [10,12]. However, these studies have mainly concentrated on low- and middle-altitude mountain areas, and cold and high-altitude regions—where the germination and growth of vegetation are limited by low temperature, insufficient water, and nutrients—have rarely been reported [13].

In alpine and subalpine areas, the natural succession of cut rock slopes is close to the primary succession [14]. As the pioneer species of primary succession and the dominant species of biological soil crusts, mosses play an extremely important role in degraded habitats [15,16]. Moss–soil crusts are an organic complex resulting from an intimate association between soil particles and cyanobacteria, algae, microfungi, lichens, and mosses, which are the most advanced stage of biological soil crusts [17–19]. Due to their extensive adaptability and strong reproductive capacity, mosses can survive in grassland, cultivated land, northern forest, mountain rainforest, alpine environments, tundra, desert, and other habitats [20]. The development of mosses in different habitats is heterogeneous in species composition, growth rate, and community structure (coverage and biomass) [21–24]. Many factors could be responsible for the difference, such as slope aspect, elevation, and time, which have been shown to significantly affect moss development [24,25]. Previous studies have shown that moss is of great significance in promoting restoration of cut rock slopes, which is consistent with the periodic law of vegetation succession and conducive to long-term sustainable development [26]. Similarly, the dominant species and development degree of moss crusts would be different on slopes with different terrain, climate, and other environmental conditions [27]. Nevertheless, the basic research of moss–soil crusts on cut rock slopes—particularly in alpine areas, where the mosses are the main component of ground cover plants—is still lacking.

Large mountainous areas are distributed in China, accounting for two-thirds of the national territory, particularly in western China [28]. The mountainous area in western Sichuan, Southwest China is an ideal place to study natural ecological restoration, as many exposed cut rock slopes exist due to engineering construction and it is difficult to implement manual restoration on the steep slopes of high mountains. Furthermore, the varied natural geographic features (e.g., climate, lithology, terrain, etc.) in this area might be beneficial to explore the geographical effect on moss–soil crust restoration. In this paper, moss coverage and biomass, soil weight, and major nutrient properties were investigated during the restoration of moss–soil crusts on cut rock slopes in western Sichuan to understand the impact of aspect, elevation, lithology, and time on restoration. The aims of this study are to (1) analyze the features of moss–soil crusts on cut rock slopes under different geographical conditions and (2) address the influence of geographical factors on the development of moss–soil crusts on cut rock slopes in alpine and subalpine areas to provide a scientific basis for the implementation of ecological restoration on cut rock slopes in mountainous regions.

2. Materials and Methods

2.1. Study Sites

This study was carried out in western Sichuan, the hinterland of Southwest China (26°03′–34°19′ N, 97°21′–108°12′ E) (Figure 1). Since different geographic locations may have different environmental conditions, a general research area related to climatic differences was defined according to geographic location within the study area: (1) In the Baoxing sampling area, the altitude ranges from 1942 to 4166 m above sea level (a.s.l.). The subtropical–cold temperate humid monsoon climate prevails in this area, with a mean annual temperature (MAT) of less than 10 °C and a mean annual precipitation (MAP) of less than 1000 mm [29]. (2) In the Pengzhou–Shifang sampling area, the altitude lies within ~900 and 1200 m a.s.l. The subtropical humid monsoon climate controls this area, with MAT of 12–14 °C and MAP of 1000 mm or higher. (3) In the Wenchuan–Lixian sampling area, the altitude is between ~2000 and 2500 m a.s.l. This area is dominated by a warm temperate continental semiarid monsoon climate, with a MAT of 6–10 °C and MAP of 540–610 mm [30]. Due to a wide range of altitude differences and complex terrains, the climate obviously varies with increasing elevation in all sample areas. The altitude, rainfall, and other environmental factors in each sampling area are shown in Table 1. In the study area, a large area of cut rock slopes have been produced by the intensive and extensive construction of transportation and mining projects, characterized by high and steep slopes with instability.

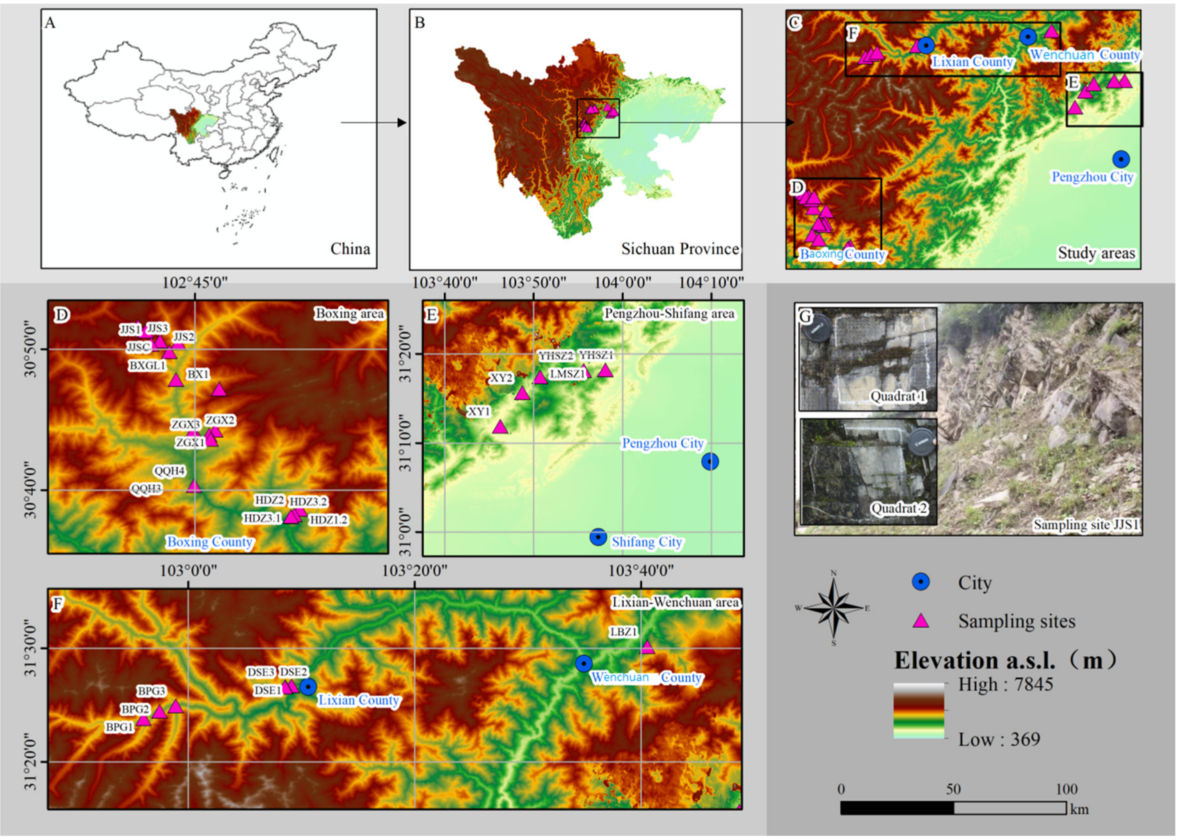

Figure 1. Study area and the distribution and selected landscape of sampling sites in the west of Sichuan, SW China.

Table 1. Climate, elevation, and vegetation of studied areas in west Sichuan's mountainous region, China.

Area	Climate	Elevation (m a.s.l.)	Mean Annual Precipitation (mm)	Typical Natural Vegetation	Plant	Topography
Baoxing	Subtropical–cold temperate humid monsoon climate	1942–4116	600–1000	Theropencedrymion, subalpine coniferous forest, alpine shrubs and meadows	Sedge, purslane, pine, cedar	Mountainous terrain
Pengzhou–Shifang	Subtropical humid monsoon climate	900–1200	1100–1500	Evergreen broad-leaved forest	Dicranopteris pedata, acorus calamus, brich	Mountainous terrain
Lixian–Wenchuan	Warm temperate continental semi-arid monsoon climate	2013–2426	540–610	Bushwood, pinus tabulaeformis	Coriaria sinica, artemisia argyi, cedar	Mountainous terrain

2.2. Field and Laboratory Methodology

2.2.1. Sample Collection

After a pilot investigation of cut rock slopes in western Sichuan between October 2017 and October 2018, a total of 335 quadrats on 35 cut rock slopes were chosen for further detailed study (Figure 1), of which 250, 49, and 36 quadrats were surveyed in the Baoxing, Pengzhou–Shifang and Wenchuan–Lixian areas, respectively (Table 2). On each cut rock slope, the surrounding environment was investigated, and the basic conditions of the cut rock slopes were also recorded, e.g., geographic coordinates, elevation, aspect, and height. The formation age of the cut rock slopes was obtained through data review and field investigation. This duration may also be regarded as the restoration age of those slopes because the natural rebuild process started when the slopes were formed and human disturbance ended.

Within each cut rock slope, quadrats with an area of 20 cm × 20 cm were established, and the number of quadrats was determined by the size of the cut rock slopes. Before sample collection, each quadrat was imaged using a camera to estimate the area of the crusts. The samples of moss–soil crusts were obtained with sterilized tweezers and collecting knives to separate the crusts from the rock surface. The dead branches and fallen leaves on the surface of the crusts were picked out, while soil samples were separated from mosses in the crusts. After collection, these samples were put into polyethylene bags and then immediately transferred to the laboratory for sample processing.

2.2.2. Preparation and Analysis of Samples

ArcGIS10.2 and ENVI5.3 software were used to extract the moss–soil crust coverage from the images for each quadrat, utilizing a supervised fuzzy clustering approach and visual interpretation [31]. Moss biomass in the crusts was determined by the sieve washing method. After cleaning with water, the mosses were dried to a constant weight at 65 °C for 48 h, and the dried mosses were weighed with a balance (model PTX-FA110) to calculate the moss biomass per unit area.

The air-dried soil samples, after removing plant residue, were crushed and ground in an agate mortar. The soils were passed through a 100-mesh sieve and preserved for use. More than 50% of the soil samples in the quadrats in this study were less than 10 g in weight. The contents of soil organic matter (SOM), total nitrogen (TN), and total phosphorus (TP) were measured by the potassium dichromate oxidation method, semimicro-Kjeldahl method, and sodium hydroxide melting–molybdenum antimony colorimetric method [32]. Soil TN and TP in 132 and 75 quadrats could not be determined due to the lack of soils.

Table 2. General geographical description at sampling sites in western Sichuan's mountainous region, China.

Area	Sample Site ID	Number of Sample Quadrats	Latitude and Longitude of Sampling Sites	Elevation (m a.s.l.)	Restoration Age (Year)	Slope Angle (°)	Slope Aspect	Slope Length (m)	Slope Height (m)
Baoxing	BX1	15	25°07′90″ N, 102°46′45″ E	2036	9	90	N	5	10
	BXGL1	19	30°47′50″ N, 102°43′40″ E	2430	~30	85	N	9	12
	JJSA	18	30°51′38″ N, 102°40′57″ E	4116	3	70	S	35	3
	JJSB	8	30°51′16″ N, 102°41′32″ E	3880	3	75	S	15	6
	JJSC	25	30°50′34″ N, 102°42′32″ E	3716	8	76	S	35	8
	JJS1	12	30°50′20″ N, 102°41′54″ E	3448	8	90	N	40	8
	JJS2	14	30°49′48″ N, 102°43′12″ E	3187	8	80	N	200	15
	JJS3	8	30°50′26″ N, 102°43′50″ E	2878	8	85	S	150	30
	ZGX1	15	30°44′14″ N, 102°46′27″ E	2816	5	78	S	30	8
	ZGX2	18	30°43′55″ N, 102°46′01″ E	2640	5	71	S	100	5
	ZGX3	13	30°43′35″ N, 103°46′08″ E	2430	5	85	N	60	20
	QQH2.1	10	30°44′11″ N, 102°44′56″ E	2166	13	85	S	13	9
	QQH2.2	6	30°44′04″ N, 102°44′51″ E	2166	13	80	N	30	9
	QQH3	12	30°41′22″ N, 102°43′21″ E	2182	15	70	N	60	50
	QQH4	4	30°40′18″ N, 102°44′54″ E	2024	15	75	N	25	30
	HDZ1.1	13	30°38′37″ N, 102°52′30″ E	2353	27	83	N	27	11
	HDZ1.2	17	30°38′37″ N, 102°52′30″ E	2353	27	90	S	30	20
	HDZ2	9	30°38′14″ N, 102°52′06″ E	2227	27	76	N	8	15
	HDZ3.1	12	30°38′05″ N, 102°51′51″ E	1942	27	77	N	20	7.5
	HDZ3.2	6	30°38′07″ N, 102°51′51″ E	1942	27	85	S	7	2.5
Pengzhou–Shifang	XY1	11	31°11′52″ N, 103°46′16″ E	1043	2.5	88	S	10	2
	XY2	9	31°15′38″ N, 103°48′45″ E	967	4	68	N	3	5
	LMSZ1	12	31°17′26″ N, 103°50′44″ E	1177	>60	78	S	8	5
	YHSZ1	14	31°18′13″ N, 103°58′05″ E	1003	1.5	64	N	10	6
	YHSZ2	3	31°18′08″ N, 103°55′38″ E	1124	<0.5	85	S	12	7

Table 2. *Cont.*

Area	Sample Site ID	Number of Sample Quadrats	Latitude and Longitude of Sampling Sites	Elevation (m a.s.l.)	Restoration Age (Year)	Slope Angle (°)	Slope Aspect	Slope Length (m)	Slope Height (m)
Wenchuan–Lixian	LBZ1	5	31°30′08″ N, 103°40′36″ E	2013	2	90	N	5	5
	DSE1	3	31°26′42″ N, 103°40′36″ E	2032	7	80	N	3	20
	DSE2	5	31°26′35″ N, 103°08′35″ E	2081	7	70	N	7	6
	DSE3	6	31°26′34″ N, 103°08′33″ E	2145	7	50	N	12	8
	BPG1	6	31°23′48″ N, 102°56′03″ E	2426	49	60	S	8	16
	BPG2	5	31°24′27″ N, 102°57′28″ E	2350	49	84	S	7	8
	BPG3	6	31°24′54″ N, 102°58′54″ E	2290	49	90	S	20	9

The soil nutrient stock (SNS) ($g \cdot m^{-2}$) is the product of soil weight and nutrient content. Therefore, the SNT can be defined as:

$$SNS_i = (C_i \times SW_i)/S \quad (1)$$

where C_i, SW_i, S, and i represent the nutrient content in the investigated soils ($g \cdot kg^{-1}$), the soil weight in each quadrat (kg), the sampling area (0.04 m^2), and the measured nutrient, respectively.

2.2.3. Statistical Analysis

Correlation coefficient analysis was used to estimate the relationship between moss and soil characteristics. Multivariate analysis of variance was used to test the significance of variations in moss biomass and soil major nutrients under different lithologies and slope aspects. Principal component analysis (PCA) was used to reduce the dimension of recovery feature indicators of moss–soil crusts. There were several quadrats at each sample point, and other geographical factors were fixed when discussing the influence of factor. The data we tested are normally distributed. One-way analysis of variance (ANOVA) was used to test the significance of variations in moss biomass and soil major nutrients under different elevations and formation ages. The criteria for significance in the procedures were set at $p < 0.05$ (significance) and $p < 0.01$ (high significance). IBM SPSS 16.0 was used for statistical analysis, and Microsoft Excel 2010 and Origin 2018 were used for data editing and visualization.

3. Results

3.1. Coverage and Biomass of Moss–Soil Crusts on Cut Rock Slopes

Across the study area, moss coverage of the crusts fluctuated greatly, ranging from 0 to 90% (Table 3). Moss coverage at the sampling sites in the Baoxing area ranged from 0.42% to 83.79%, with a mean value of 24.12%, and more than 60% of quadrats had less than the mean value. Only at two sample sites (HDZ1.1 and HDZ2) with a formation age of 27 years was the average moss–soil crust coverage greater than 50%. Moss coverage at the sampling sites in the Pengzhou–Shifang area varied from 0 to 66.91%, with a mean value of 15.64%. The maximum coverage appeared on the cut rock slope with a formation age higher than 60 years (Site LMSZ1), and the cut rock slope with a restoration age lower than 0.5 years had almost no moss crusts (Site YHSZ2). Moreover, moss crusts in the Wenchuan–Lixian area varied between 5% and 90%.

Table 3. Moss coverage and biomass within the crusts in three study areas.

Areas	Baoxing		Pengzhou–Shifang		Wenchuan–Lixian	
Variables	Moss Coverage (%)	Moss Biomass ($g \cdot m^{-2}$)	Moss Coverage (%)	Moss Biomass ($g \cdot m^{-2}$)	Moss Coverage (%)	Moss Biomass ($g \cdot m^{-2}$)
Maximum	83.97	888.50	66.91	210.44	90.00	220.00
Minimum	0.42	0.25	0	0	5.00	0.48
Mean	24.12	97.03	15.64	28.48	43.33	43.62
Standard deviation	18.36	131.24	16.07	39.51	21.68	58.74
Sample number	250	250	49	49	36	36

The biomass of moss crusts in the study areas also changed dramatically, with a standard deviation greater than the average value (Table 3). Especially in the Baoxing area, the moss biomass value varied greatly within a range of 0.25 to 888.50 $g \cdot m^{-2}$. The mean value of biomass in the Pengzhou–Shifang area was 28.48 $g \cdot m^{-2}$, with values between 0 and 210.44 $g \cdot m^{-2}$. Consistent with the coverage, the maximum biomass value appeared on the same cut rock slopes, which were distributed at the sites (HDZ1.1 and HDZ2) with a restoration age of 27 years in the Baoxing area and at the site (LMSZ1) with a restoration age of more than 60 years in the Pengzhou–Shifang area. In the Wenchuan–Lixian area, the biomass value oscillated from 0.48 to 220.00 $g \cdot m^{-2}$, with an average of 43.62 $g \cdot m^{-2}$. Moss coverage was highly positively correlated with moss biomass in all quadrats ($p < 0.01$, r = 0.502, n = 335, Figure 2).

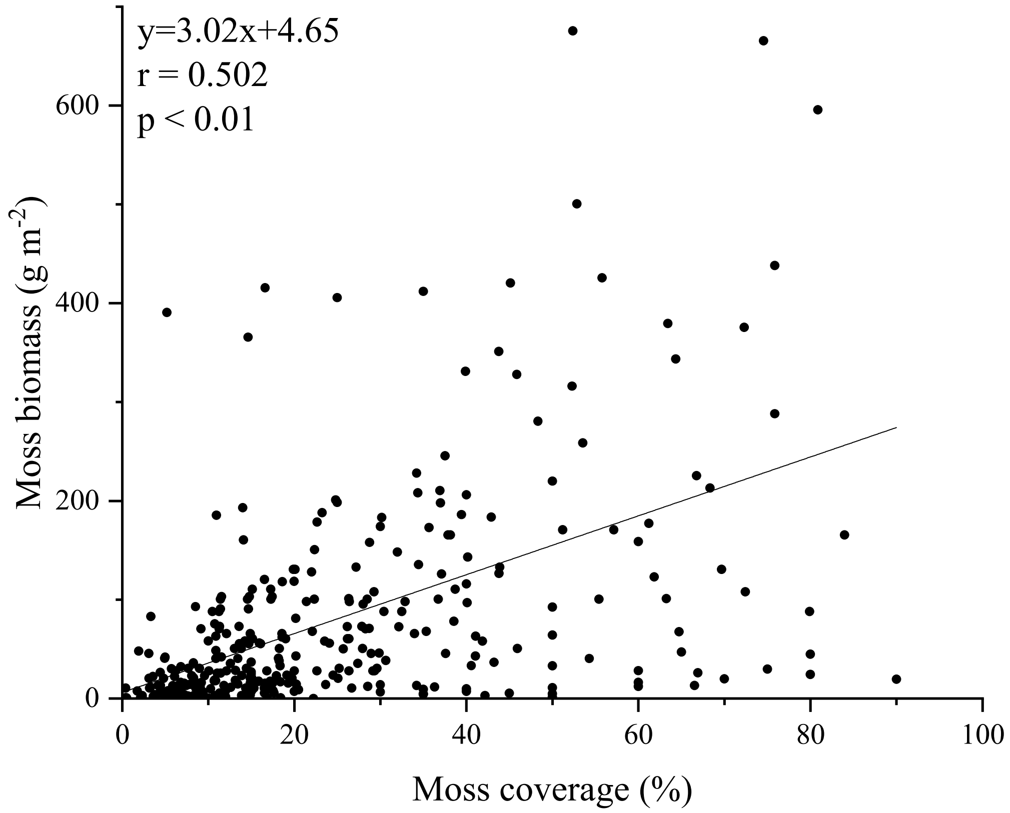

Figure 2. Plots between moss coverage and moss biomass in the natural restoration process on cut rock slopes in west Sichuan's mountainous region.

3.2. *Soil Weight within Moss–Soil Crusts on Cut Rock Slopes*

Due to human disturbance and relatively shorter weathering times (less than 100 years), cut rock slopes commonly lack soils derived from rock weathering [33]. In this study, the soil weight in moss–soil crusts was low, varying within 0 and 4.79 kg·m^{-2} (Table 4). Six percent of the quadrats were observed without soil in the crusts. The soil weights in the Baoxing, Pengzhou–Shifang, and Wenchuan–Lixian areas ranged from 0 to 4.77 kg·m^{-2}, 0 to 4.51 kg·m^{-2}, and 0.02 to 4.79 kg·m^{-2}, respectively. The standard deviation was greater than or close to the average value, indicating the uneven distribution of soils on cut rock slopes. Soil weight was highly positively correlated with moss coverage ($p < 0.01$, r = 0.218, Table 5) and moss biomass ($p < 0.01$, r = 0.188, Table 5). Combined with the correlation between moss coverage and biomass, the results showed interaction between the mosses and soils which jointly promoted the development of the moss–soil crusts.

Table 4. Soil weight and major nutrient contents within the crusts in different areas of western Sichuan's mountainous region.

Areas	Variables	SW (kg·m^{-2})	SOM (g·kg^{-1})	TP (g·kg^{-1})	TN (g·kg^{-1})	S_{OM} (g·m^{-2})	S_P (g·m^{-2})	S_N (g·m^{-2})
Baoxing	Maximum	4.77	377.42	5.05	5.24	361.17	6.65	5.05
	Minimum	0	5.24	0.02	0.07	0.04	0.01	0.01
	Mean	0.43	86.32	0.72	1.69	24.87	0.33	0.91
	Standard deviation	0.67	71.96	0.59	0.90	34.01	0.61	1.00
	Sample number	250	211	182	125	211	182	125
Pengzhou–Shifang	Maximum	4.51	206.84	1.37	5.99	574.99	4.10	19.92
	Minimum	0	10.59	0.15	0.81	7.31	0.13	0.34
	Mean	0.98	99.63	0.76	2.23	96.45	0.83	4.11
	Standard deviation	1.01	57.29	0.28	1.49	111.92	0.84	5.73
	Sample number	49	46	39	21	46	39	21
Wenchuan–Lixian	Maximum	4.79	129.84	1.50	3.93	333.04	3.51	17.60
	Minimum	0.02	7.70	0.41	0.13	5.28	0.02	0.07
	Mean	0.84	62.19	0.84	2.07	47.49	0.70	2.02
	Standard deviation	1.03	34.61	0.23	1.09	66.45	0.83	3.68
	Sample number	36	32	28	25	32	28	25

SW: soil weight; SOM: soil organic content; TP: total phosphorus; TN: total nitrogen; S_{OM}: total organic stock; S_P: total phosphorus stock; S_N: total nitrogen stock.

Table 5. Pearson correlation coefficients for moss coverage, biomass, and major soil nutrients within crusts.

	CV	MB	SW	SOM	TP	TN	S_{OM}	S_P	S_N
CV	1								
MB	0.502 **	1							
SW	0.218 **	0.188 **	1						
SOM	0.188 **	0.141 *	−0.282 **	1					
TP	0.076	0.032	−0.089	0.051	1				
TN	0.091	0.108	0.008	0.478 **	0.074	1			
S_{OM}	0.141 *	0.143 *	0.675 **	0.147 *	−0.025	0.422 **	1		
S_P	0.263 **	0.142 *	0.668 **	−0.160 *	0.468 **	0.059	0.567 **	1	
S_N	0.272 **	0.128	0.716 **	0.130	−0.012	0.491 **	0.918 **	0.604 **	1

* $p < 0.05$; ** $p < 0.01$. CV: moss coverage; MB: moss biomass; SW: soil weight; SOM: soil organic content; TP: total phosphorus content; TN: total nitrogen content; S_{OM}: total organic stock; S_P: total phosphorus stock; S_N: total nitrogen stock.

3.3. Soil Major Nutrient Contents within Moss–Soil Crusts

As shown in Table 4, the content of the soil's major nutrients differed broadly. The SOM content in the Baoxing area ranged from 5.24 to 377.42 g·kg^{-1}, with an average of 86.32 g·kg^{-1}. The SOM content in the Pengzhou–Shifang area ranged from 10.59 to 206.84 g·kg^{-1}. In addition, the SOM content in the Wenchuan–Lixian area ranged between 7.7 and 129.84 g·kg^{-1}.

The mean TN contents in soils within the crusts sampled from the Baoxing, Pengzhou–Shifang, and Wenchuan–Lixian areas were 1.69, 0.76, and 0.84 $g \cdot kg^{-1}$, respectively (Table 4). Specifically, the maximum TN content appeared on the cut rock slopes with the longest formation ages, which were 30, 60, and 49 years in the Baoxing, Pengzhou–Shifang, Wenchuan–Lixian regions, respectively. The TN content was highly positively correlated with the SOM content ($p < 0.01$, r = 0.478, Table 5).

The TP content in the Baoxing, Pengzhou–Shifang, and Wenchuan–Lixian areas ranged from 0.02 to 5.05 $g \cdot kg^{-1}$, 0.15 to 1.37 $g \cdot kg^{-1}$, and 0.41 to 1.50 $g \cdot kg^{-1}$, respectively (Figure 4).

3.4. Major Soil Nutrient Stocks within Moss–Soil Crusts

The SOM stocks within the crusts varied broadly (Table 4). Particularly in the Baoxing area, the stocks of SOM were between 0.04 and 361.17 $g \cdot m^{-2}$, with an average of 24.87 $g \cdot kg^{-1}$. The mean values of SOM stocks in the Pengzhou–Shifang and Wenchuan–Lixian areas were 96.45 and 47.49 $g \cdot m^{-2}$, respectively. The maximum stocks also appeared on the cut rock slopes with the longest formation ages, which were 30 and 60 years in the Baoxing and Pengzhou–Shifang areas, respectively. In particular, the maximum SOM stock in the Wenchuan–Lixian area occurred on the cut rock slope with abnormally high soil weight at the site DSE3.

The soil N stocks in the Baoxing, Pengzhou–Shifang, and Wenchuan–Lixian areas ranged from 0.01 to 5.05 $g \cdot m^{-2}$, 0.34 to 19.92 $g \cdot m^{-2}$, and 0.07 to 17.60 $g \cdot m^{-2}$, respectively (Table 4). There was an insignificant difference in soil N stocks between the sampling sites in different areas, except for the two sites (i.e., QQH4 in Baoxing and DSE3 in Wenchuan–Lixian). The differences at these two sites resulted from the abnormal TN content or soil weight. The N stocks were highly positively correlated with the soil weight ($p < 0.01$, Table 5).

The soil P stocks in the Baoxing, Pengzhou–Shifang, and Wenchuan–Lixian areas ranged from 0.01 to 6.65 $g \cdot m^{-2}$, 0.13 to 4.10 $g \cdot m^{-2}$, and 0.02 to 3.51 $g \cdot m^{-2}$, respectively (Table 4). There was no significant difference in soil P stocks between sampling sites in different regions, except for one site (DSE3) in the Wenchuan–Lixian area, which was related to the high soil weight.

3.5. Principal Component Analysis (PCA)

The PCA results for the nine characteristics of naturally restored moss–soil crusts are shown in Table 6. The contributions of principal components PC1, PC2, PC3, and PC4 to the variation were 42.75%, 18.25%, 13.85%, and 12.83%, respectively, accounting for 87.7% of the total variation value, indicating that these four principal components could explain the majority of the variation in the ecological restoration characteristics of moss–soil crusts. The variables with the highest loading in PC1 were soil weight, SOM stock, P stock, and N stock. Soil weight had a higher loading score in PC1, and was selected as the single indicator of PC1, as all the other preselected variables were related to it ($p < 0.01$, Table 5). For PC2 the selected indicator was TP content. In PC3 the variables, e.g., SOM and TN contents, showed the highest loadings on this axis (Table 6). TN content was chosen as the indicator since it was significantly correlated with the other preselected variables in PC3 ($p < 0.01$, r = 0.478, Table 5) and had the highest loading. Finally, in PC4 moss coverage and moss biomass had the highest loading, and moss biomass was selected as the indicator due to its significant correlation with moss coverage ($p < 0.01$, r = 0.502, Figure 2, Table 5) and the higher loading in the PCA.

Table 6. Loading coefficients of the variables analyzed for the principal components (PC) that comply with the condition of λ > 1.

Variables	Principal Component (PC)			
	PC1	**PC2**	**PC3**	**PC4**
CV	0.48	0.13	0.01	**0.68**
MB	0.34	0.02	0.16	***<u>0.83</u>***
SW	***<u>0.84</u>***	−0.23	−0.40	0.01
SOM	0.10	−0.13	**0.74**	0.15
TP	0.22	***<u>0.93</u>***	0.18	−0.12
TN	0.29	−0.16	***<u>0.86</u>***	−0.13
S_{OM}	**0.87**	−0.30	0.18	−0.18
S_P	**0.84**	0.42	−0.17	−0.11
S_N	**0.89**	−0.29	0.14	−0.21
Cumulative variance (%)	42.75	18.25	13.85	12.83

In bold, for each PC, are the variables that comply with the condition of belonging to the range of loadings between the maximum absolute value and 10%. The variables in italic and the underlined loading values identify the indicators selected taking into account Pearson's bivariate correlations ($p < 0.05$).

4. Discussion

Geographical variables, such as lithotype, microclimate, rainfall, and time—of which, microclimatic factors, such as temperature and humidity, are more relevant than others—exert substantial effects on the development of mosses [24,34,35]. In particular, humidity is a key factor in moss development since water availability is an important component of the key ecophysiological processes in mosses [36]. Given that the environmental variables in the field are difficult to define, the elevation and slope aspect—which are readily quantitatively characterized—might represent the changes in climate factors, such as humidity and temperature. Due to the strong correlation between many environmental variables, we try to fix other geographical factors, in addition to the factors discussed, to better distinguish the influence of factors. Here, we would discuss the effect of elevation, slope aspect, lithology, and formation age on the evolution of moss–soil crusts.

4.1. Influence of Aspect and Lithology on the Natural Restoration of Moss–Soil Crusts on Cut Rock Slopes

An insignificant influence of slope aspect on moss biomass was observed in this study (Figure 3A), although higher moss biomass appeared on north-facing slopes (91.19 ± 136.90 g·m^{-2}) than on south-facing slopes (64.78 ± 86.34 g·m^{-2}), consistent with a previous report [37]. However, the aspect of cut rock slopes had a strong influence on soil weight. The soil weight within the crusts on south-facing slopes was significantly higher than that on north-facing slopes (Figure 3B), depending on the provenance of the soils. It is well known that the development of soils on steep slopes derived from hard bedrock is often very slow, and the estimated production rate of soils developed on granite was 1 m per 20,000 years [38]. At the initial stage of formation on cut rock slopes, the soils in the crusts were absent due to artificial disturbance. In this study, there was little soil on the cut rock slope by the restoration time of 0.5 years, whereas the soil weight reached 0.76 kg·m^{-2} with the restoration time ranging to 1.5 years. This implied that the soils in the crusts on the cut rock slopes likely came from trapping the existing soils, especially from hill tops, other than in situ rock-weathering products. Furthermore, driven by the higher moisture content and temperature, the weathering intensity on the south-facing slopes was much stronger, including physical weathering, relative to that on the north-facing slopes, resulting in more weathering products and cracks on the south-facing slopes 40 [39]. More weather products and weathering cracks might facilitate providing more soil mass and trapping more grains, leading to the higher soil weight on the south-facing slopes.

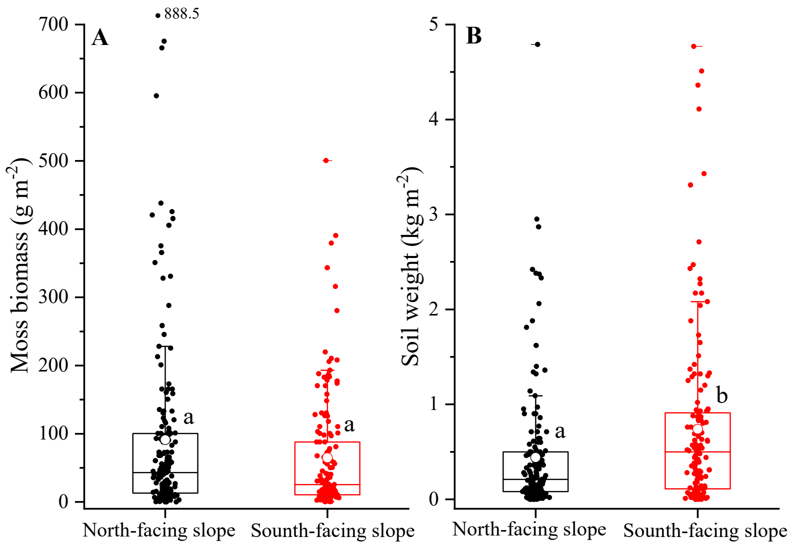

Figure 3. Moss biomass (**A**) and soil weight (**B**) in moss–soil crusts on north-facing and south-facing cut rock slopes in west Sichuan mountainous region. Different letters represent significant difference at $p < 0.05$ between two slope aspects.

The type of crust substrate might affect the development of mosses [40]. In this study, the difference in lithological substrate (i.e., limestone and sandstone) appeared to be the determining factor in moss growth and soil accumulation (Figure 4A). The mean value of moss biomass on a cut rock slope of limestone (96.31 g·m^{-2}) was 1.64 times higher than that of sandstone (58.71 g·m^{-2}). It was previously shown that more abundant mosses, including the number of species and coverage, were distributed on limestone than non-limestone (sandstone) at each site in Eastern Australia, which was attributed to the rock moisture and surface properties [41]. Deep crevices existed between massive limestone outcrops, allowing runoff and subsequent accumulation of water in hollows and crevices. Moreover, the chemical properties of the rock surface also seemed to be a significant factor in the distribution of mosses on limestones. Calciophilic mosses prefer to grow on limestone but are unable to survive on non-limestone [42,43].

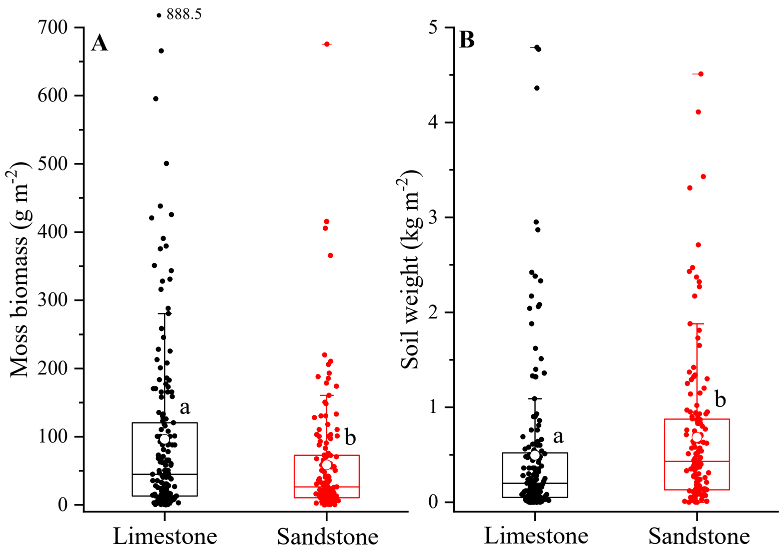

Figure 4. Moss biomass (**A**) and soil weight (**B**) in moss–soil crusts of cut rock slopes developed on limestone and sandstone in west Sichuan mountainous region. Different letters represent significant difference at $p < 0.05$ between limestone and sandstone.

The soil weight on sandstone was higher than that on limestone, especially on the south-facing slopes (Figure 4B). This could be related to the higher weathering intensity on sandstone. The formation rate of the weathered soil layer in the limestone area is 0.1–0.4 cm per thousand years in the humid region [44], in contrast with 0.7 to 1.8 cm per thousand years on the vertical surfaces of sandstone even under the semiarid climate in southern Jordan [45].

4.2. Influence of Elevation on Moss Development on Cut Rock Slopes

In fact, the altitude gradient, to a large extent, reflects the difference in climatic conditions, such as precipitation, temperature, and sunshine [46]. The results showed that there was a significant difference in moss biomass among different altitudes (Figure 5). In this study, we found that the variation in moss biomass with altitude was also consistent with that of rainfall. In the humid area (e.g., Baoxing area), the moss biomass and rainfall increased gradually along with the elevation rise, from 1942 to 2353 m on cut rock slopes with a formation age of 5 years and from ~2400 to ~2800 m on cut rock slopes with a restoration age of 27 years (Figure 5A,B). Furthermore, the variation in moss biomass with altitude was more obvious in semiarid climate regions (e.g., the Wenchuan–Lixian area). For cut rock slopes with a formation age of 7 years, the moss biomass increased significantly when the altitude changed by only ~50 m (increased from 2032 to 2081 m) (Figure 5C). Even if the slope was restored for 49 years, the moss biomass also increased significantly with the rising elevation of only 50 m from ~2350 to ~2400 m (Figure 5D).

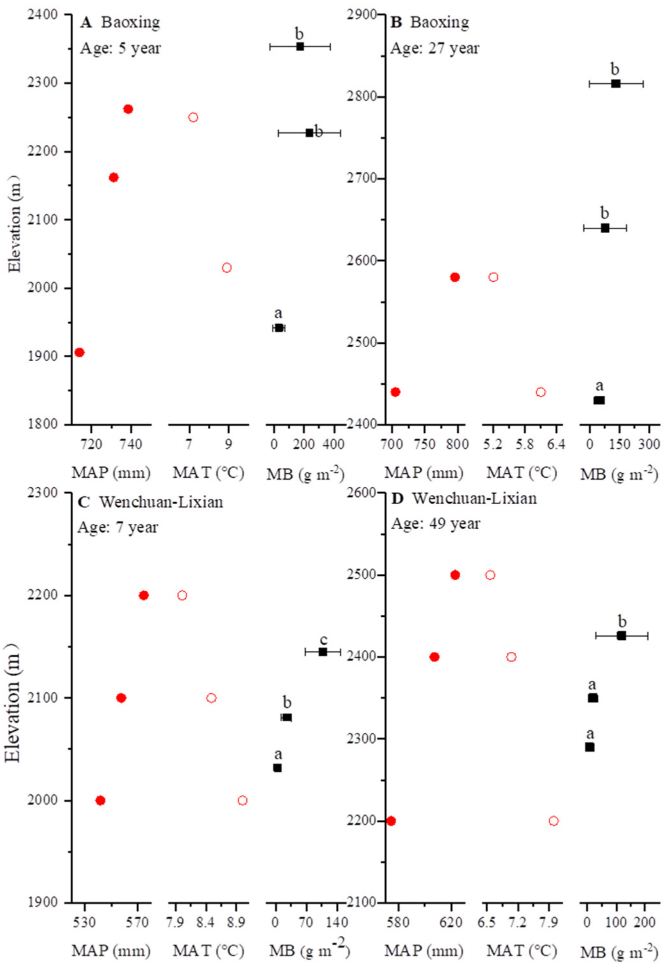

Figure 5. Variation of moss biomass with altitude in Baoxing and Wenchuan–Lixian areas. MAP: mean annual precipitation; MAT: mean annual temperature; MB: moss biomass. Different letters represent significant difference at a level of $p < 0.05$.

Previous studies have confirmed that the growth of moss is greatly affected by humidity [47], which is the most important environmental factor in the distribution of moss species on limestone [42]. Relatively humid conditions help create a better growth environment for vegetation, leading to better growth of mosses at altitudes with high rainfall [48]. A positive correlation between lichen and moss abundance and higher moisture was previously demonstrated [49]. It was also found that the moss coverage and biomass in Mount Gongga in western Sichuan increased with altitude and precipitation, while the ground moss coverage reached 95.64% at an altitude of 3750 m [50]. The moss development in the semiarid climate area was more obvious with altitude relative to that in humid regions, likely owing to the higher sensitivity of the mosses to moisture in the former than in the latter [51].

4.3. Influence of Restoration Time on Moss Development on Cut Rock Slopes

Time is one of the critical factors that affect ecosystem succession. Considering that the growth of moss is dependent on the climate and lithology, the selection of sampling quadrats developed on the lithological substrate (i.e., limestone and sandstone) and in different climatic regions (Baoxing, Pengzhou–Shifang, Wenchuan–Lixian areas) was set when the impact of time on moss development was discussed.

According to the comparison of sample sites, the moss crust increased with restoration time, while the rate of moss biomass was diverse in different geographical areas. In the Pengzhou–Shifang area, the moss reached stability quickly. After significant development of moss between the sandstone cut slope with restoration ages of 0.5 years and 1.5 years, with moss biomass increasing from 0 to 24.08 g·m^{-2} (Figure 6), there was an insignificant difference in the moss biomass with the restoration age increasing from 1.5, 2.5, and 60 years within the slightly varied elevation (1003 to 1177 m) on the cut rock slope of the same lithotype in the Pengzhou–Shifang area ($p > 0.05$) (Figure 7A). In the Baoxing area, the moss biomass also increased with the formation age on the cut rock slope when the altitude was similar. However, it would take more time for moss to develop to stability in the Baoxing area. For formation ages of 3 and 8 years (3880 and 3716 m a.s.l., sandstone), 5 and 27 years (2430 and 2353 m a.s.l., limestone), and 15 and 27 years (2182 and 2227 m a.s.l., limestone), the moss biomass on the cut rock slope increased significantly with increasing age ($p < 0.05$) (Figure 7B,C). Our pilot study showed that, on limestone cut slopes in Baoxing, after 5 to 27 years of natural restoration the linear pattern between time (T, year) and moss biomass (MB, g·m^{-2}) might be established (Figure 7C); the fitting formula was defined as follows:

$$MB = 6.4091\ T + 14.4742\ (r = 0.83, n = 7, p < 0.05) \quad (2)$$

Figure 6. Landscape of natural recovery on cut rock slopes of sandstone in Shifang: (**A**) the natural recovery age of 0.5 years at an elevation of 1124 m; (**B**) the natural recovery age of 1.5 years at an elevation of 1003 m.

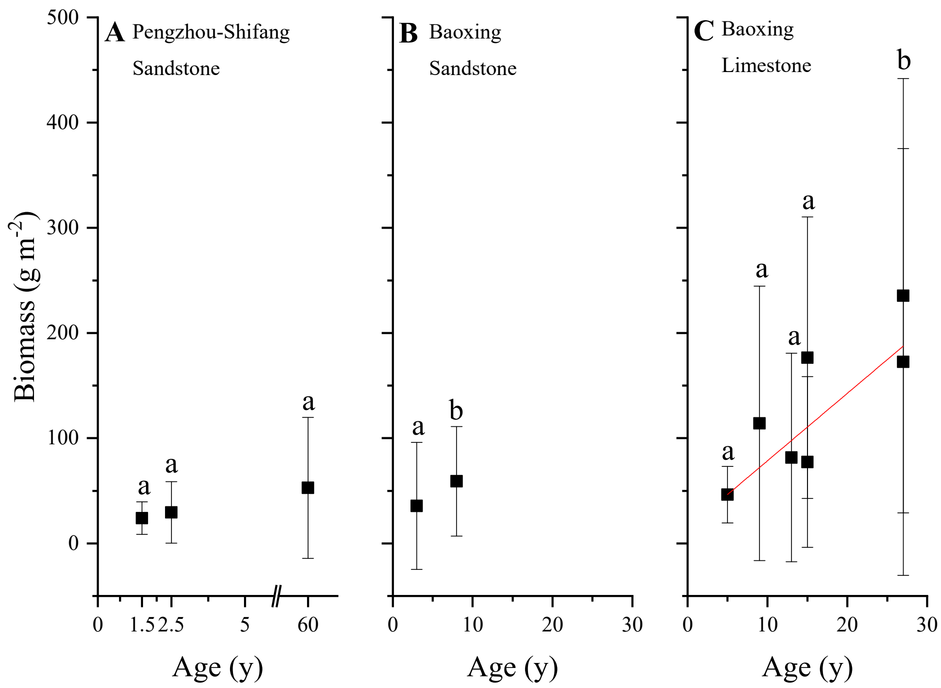

Figure 7. Variation of moss biomass with restoration age on cut rock slopes. (**A**) The altitude within 1003 and 1177 m, sandstone, Pengzhou–Shifang; (**B**) the altitude within 3716 and 3880 m, sandstone, Baoxing; (**C**) the altitude within 2024 and 2430 m, limestone, Baoxing. Different letters represent significant difference at $p < 0.05$.

The reason for the different times to reach stability of crust development between these two areas was attributed to the environmental conditions triggered by different altitudes. Due to the rapid vegetation succession in the relatively low-altitude mountainous region (~1000 m), and the growth of higher vascular plants limiting the development of moss, a stable level was quickly reached in 1.5 years (Figure 5B). However, in alpine and subalpine areas (over 2000 m a.s.l.), primitive succession is dominant; thus, the mosses are staple plants on the surface, which develop slowly and accumulate continuously [16]. For example, the biomass of lichen symbionts might reach 1892 g·m^{-2} after hundreds of years of accumulation on rocks in the polar region [52]. In Alaskan forests, moss abundance also showed an increasing tendency with time following the occurrence of fire, peaking at 30–70 years post-fire [53].

4.4. Irregular Soil Characteristics in Moss–Soil Crusts on Cut Rock Slopes during Natural Recovery

As mentioned above, the development of mosses on cut rock slopes was obviously affected by lithology, altitude, and time. However, the soil properties (e.g., soil weight and major nutrient content) in moss–soil crusts was irregular with these factors of cut rock slopes.

4.4.1. Soil Weight

The soil weight values varied with formation time of cut rock slopes. For example, the average soil weight on the cut rock slopes with the restoration age of 15 and 27 years (2024 and 1942 m a.s.l., limestone) was 0.74 kg·m^{-2} and 0.61 kg·m^{-2}, respectively (Table 7). Comparison with the values of soil weight on the cut rock slopes with different formation ages, the weight of the soils sampled from the crusts varied insignificantly ($p > 0.05$) between 2 years and 7 years (2013 and 2032 m a.s.l., limestone), 9 and 15 years (2036 and 2024 m a.s.l., limestone), 13 and 15 years (2166 and 2182 m a.s.l., limestone), 5 and 27 years (2430 and 2353 m a.s.l., limestone), 15 and 27 years (2182 and 2227 m a.s.l., limestone), 15 and 27 years (1942 and 2024 m a.s.l., limestone), and 2.5 and 60 years (1043 and 1177 m a.s.l., sandstone) (Table 7), implying the indistinctive effect of restoration age on soil accumulation. Similarly, the influence of altitude on soil weight also seemed unsystematic. This result indicates that soil weight was mainly controlled by (1) the soils on the cut rock slopes from existing mature surface soil near the crusts, especially from hill tops [33], and the slow and weakened soil development on cut rock slopes [54]; and (2) soil loss caused by multiple factors, such as water and wind erosion, microtopography, and the density and biomass moss crusts, other than restoration time and elevation [33,51,55].

Table 7. Soil weight variation with formation time under the similar altitude in different areas.

Area	Elevation (m)	Formation Age (Year)	Soil Weight (kg·m^{-2})
Baoxing	2036	9	0.18 ± 0.16 a
	2024	15	0.74 ± 0.60 a
	1942	27	0.61 ± 0.96 a
	2166	13	0.16 ± 0.08 a
	2182	15	0.49 ± 0.67 a
	2430	5	0.17 ± 0.25 a
	2353	27	0.22 ± 0.18 a
	2181	15	0.49 ± 0.66 a
	2227	27	0.18 ± 0.22 a
Pengzhou–Shifang	1043	2.5	1.43 ± 1.19 a
	1177	60	1.49 ± 1.37 a
Wenchuan–Lixian	2013	2	1.45 ± 1.03 a
	2032	7	0.16 ± 0.05 a

Different letters denote significant difference at $p < 0.05$ at different recovery times. The same letter denotes no significant difference at $p < 0.05$ at different recovery times. The contrast only occurs between two points with similar altitude.

4.4.2. Soil Major Nutrient Content

In this study, the nutrient contents in the soils on cut rock slopes were fairly high. The highest SOC and TP contents reached 377.42 g·kg^{-1} and 5.05 g·kg^{-1}, respectively (Table 4). However, the nutrient contents were less relevant to the factors such as lithology, aspect, altitude, and restoration time, possibly constrained by the material source of soil on the cut rock slope and features of moss crusts. As mentioned above, the soils within the crusts on the cut rock slopes came dominantly from the soils surrounding the crusts, which are rich in the fertility by nature [33]. Moss coverage and biomass showed significant correlations with soil nutrient contents (Table 5). In the process of natural recovery, moss development further prompts the major nutrient content of the soils within the crusts by fixing carbon and nitrogen and with self-decomposition [49,56,57].

5. Conclusions

Affected by the climate in mountainous areas, especially in alpine and subalpine areas, the natural restoration of moss–soil crusts on cut rock slopes is a long-term process with a slow rate of action. These findings unequivocally show that lithology, altitude and recovery time exerted a great impact on moss coverage and biomass, while the slope aspect had a great impact on soil weight in the crusts.

Specific selection of calciophilic mosses may lead to better adaptation of moss crusts on limestone than sandstone. The development of moss was greatly affected by water; thus, the variation trend of moss biomass with altitude was consistent with that of moss biomass with rainfall. The changes in moss development in semiarid climate areas, such as the Wenchuan–Lixian area, were more prominent with altitude. Moss biomass increased with increasing restoration age, while the restoration rate varied in different geographical areas. Vegetation succession was rapid in low-altitude areas (~1000 m); thus, there was no significant difference in moss biomass at restoration ages between 1.5 and 60 years. However, the moss biomass increased slowly in high-altitude mountain areas (~2000 m) because the areas mainly experienced primary succession with slow and sustainable development of mosses. The soils within the moss–soil crusts were affected predominantly by the surrounding soils and the crust features (moss biomass and coverage); thus, the soil major nutrient contents were high. More soils accumulated on south-facing slopes than on north-facing slopes.

The findings might offer guidance for the restoration of cut rock slopes in the future, especially in alpine and subalpine regions. Different cut rock slope faces have different geographical features, such as lithotype, rainfall, and aspect, thus the impact of these factors should be fully considered to propose appropriate management measures. Given that time is a very important factor in the natural restoration of moss–soil crusts on cut rock slopes in mountainous areas, abandoned cut rock slopes should be protected from further disturbance to shorten the ecological process of restoration. In addition, the proper increase in humidity on the rock surface could be helpful for the development of moss–soil crusts.

Author Contributions: Conceptualization, C.H., W.P. and J.D.; methodology, C.H., W.P. and M.Z.; software, Y.L., W.P. and M.Z.; formal analysis, W.P. and J.D.; investigation, W.P. and M.Z.; resources, Y.L.; data curation, W.P. and Y.L.; writing—original draft preparation, W.P.; writing—review and editing, C.H.; visualization, W.P. and Y.L.; supervision, C.H. and J.D.; project administration, C.H. and J.D.; funding acquisition, C.H. All authors have read and agreed to the published version of the manuscript.

Funding: This work was funded by National Key Research and Development Program of China (2017YFC0504902) and Project of Assessment on Post-quake Ecosystem and Environment Recovery in Jiuzhaigou (5132202020000046).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data of this study are available from the authors upon request.

Acknowledgments: The authors sincerely thank the handling editor for coordinating the review of our manuscript. The authors also acknowledge anonymous reviewers for their feedback, which certainly improved the clarity and quality of this paper.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Xu, H.; Li, T.; Chen, J.; Liu, C.; Zhou, X.; Xia, L. Characteristics and applications of ecological soil substrate for rocky slope vegetation in cold and high-altitude areas. *Sci. Total. Environ.* **2017**, *609*, 446–455. [CrossRef] [PubMed]
2. Moreno-de Las Heras, M.; Nicolau, J.M.; Espigares, T. Vegetation succession in reclaimed coal-mining slopes in a Mediterranean-dry environment. *Ecol. Eng.* **2008**, *2*, 168–178. [CrossRef]
3. Zhao, M.Q.; Pu, W.Q.; LIiu, W.H.; Huang, C.M. Restoration of "vegetation-soil" system on rock-cut slope: Influencing factors and ecological succession process. *Environ. Ecol.* **2020**, *2*, 1–11.
4. Wang, M.; Liu, Q.; Pang, X. Evaluating ecological effects of roadside slope restoration techniques: A global meta-analysis. *J. Environ. Manag.* **2021**, *281*, 111867. [CrossRef]
5. Gao, G.J.; Yuan, J.G.; Han, R.H.; Guo, R. Characteristics of the optimum combination of synthetic soils by plant and soil properties used for rock slope restoration. *Ecol. Eng.* **2007**, *30*, 303–311. [CrossRef]
6. Tekle, K. Natural regeneration of degraded hillslopes in Southern Wello, Ethiopia: A study based on permanent plots. *Appl. Geogr.* **2001**, *3*, 275–300. [CrossRef]
7. Sampiao, G.; Nobre, C.; Costa, M.H.; Satyamurty, P.; Soares-Filho, B.S.; Cardoso, M. Regional climate change over eastern Amazonia caused by pasture and soybean cropland expansion. *Geophys. Res. Lett.* **2007**, *17*, 251–270. [CrossRef]
8. Khater, C. Spontaneous vegetation dynamics and restoration prospects for limestone quarries in Lebanon. *Appl. Veg. Sci.* **2003**, *6*, 199–204. [CrossRef]
9. Duan, W.; Ren, H.; Fu, S.; Wang, J.; Yang, L.; Zhang, J. Natural recovery of different areas of a deserted quarry in South China. *J. Environ. Sci.* **2008**, *20*, 476–481. [CrossRef]
10. Bochet, E.; García-Fayos, P. Factors Controlling Vegetation Establishment and Water Erosion on Motorway Slopes in Valencia, Spain. *Restor. Ecol.* **2004**, *12*, 166–174. [CrossRef]
11. Walker, L.R.; Moral, R.D. *Primary Succession and Ecosystem Rehabilitation*; Cambridge University Press: Cambridge, UK, 2003; p. 340.
12. Zhao, X.; Wang, J.; Zhao, D.; Triantafilis, J. Soil organic carbon prediction by multi-digital data fusion for nitrogen management in a sugarcane field. *Nutr. Cycl. Agroecosyst.* **2022**, 1–18. [CrossRef]

13. Xu, H.; Li, T.; Zhou, X.; Zhang, R. Field tests on JYC ecological base material for slope protection in high-cold areas. *Chin. J. Geotech. Eng.* **2009**, *5*, 799–804.
14. Domaschuk, L. The permafrost environment. *N. Z. Geogr.* **2010**, *2*, 112. [CrossRef]
15. Durrell, L.; Shields, L.M. Characteristics of soil algae relation to crust formation. *Trans. Am. Microbiol. Soc.* **1961**, *80*, 73–79. [CrossRef]
16. Wu, Y.; Cheng, G.; Gao, Q. Bryophyte's ecology functions and its significances in revegetation. *J. Desert Res.* **2003**, *23*, 28–39.
17. Zhua, X. Pedogenesis of primitive soil. *Res. Soil Water Conserv.* **1995**, *2*, 919–927.
18. Belnap, J.; Büdel, B.; Lange, O.L. Biological Soil Crusts: Characteristics and Distribution. *IEEE Antennas Wirel. Propag. Lett.* **2003**, *4*, 1299–1301.
19. Chamizo, S.; Cantón, Y.; Miralles, I.; Domingo, F. Biological soil crust development affects physicochemical characteristics of soil surface in semiarid ecosystems. *Soil Biol. Biochem.* **2012**, *49*, 96–105. [CrossRef]
20. Ross-Davis, A.; Frego, K.A. Propagule sources of forest floor bryophytes: Spatiotemporal compositional patterns. *Bryologist* **2004**, *107*, 88–97. [CrossRef]
21. Müller, J.; Boch, S.; Prati, D.; Socher, S.A.; Pommer, U.; Hessenmöller, D.; Schall, P. Effects of forest management on bryophyte species richness in Central European forests. *For. Ecol. Manag.* **2019**, *432*, 850–859. [CrossRef]
22. Humphrey, J.W.; Davey, S.; Peace, A.J.; Ferris, R.; Harding, K. Lichens and bryophyte communities of planted and semi-natural forests in Britain: The influence of site type, stand structure and dead wood. *Biol. Conserv.* **2002**, *170*, 165–180. [CrossRef]
23. Rehm, E.M.; Thomas, M.K.; Yelenik, S.G.; Bouck, D.L.; D'Antonio, C.M. Bryophyte abundance, composition and importance to woody plant recruitment in natural and restoration forests. *For. Ecol. Manag.* **2019**, *444*, 405–413. [CrossRef]
24. Luis, L.; Bergamini, A.; Sim-Sim, M. Which environmental factors best explain variation of species richness and composition of stream bryophytes? A case study from mountainous streams in Madeira Island. *Aquat. Bot.* **2015**, *123*, 37–46. [CrossRef]
25. Wang, Q.; Wu, N.; Luo, P.; Yi, S.; Bao, W.; Shi, F. Moss growth rare and its environmental determinants in subalpine coniferous forest and clear-cut land in Eastern Tibetan plateau, China. *J. Plant Ecol.* **2007**, *3*, 464–469.
26. Zuo, Y.; Gu, B.; Ai, Y. Investigation of application of bryophyte to road side ecological restoration. *Sci. Soil Water Conserv.* **2006**, *4*, 122–125.
27. Concostrina-Zubiri, L.; Arenas, J.M.; Martínez, I.; Escudero, A. Unassisted establishment of biological soil crusts on dryland road slopes. *Web Ecol.* **2019**, *19*, 39–51. [CrossRef]
28. Chen, G. Some considerations on strategy of development of mountain regions of China. *Bull. Chin. Acad. Sci.* **2007**, *22*, 126–131.
29. Wang, L.; Ma, L. Spatial-temporal distribution characteristics of short-period heavy precipitation in Baoxing of Sichuan. *Meteorol. Sci. Technol.* **2016**, *44*, 423–429.
30. Zhang, Y.; Zhang, Z.; He, Y. Distribution of climatic elements in the Upper Reaches of Minjiang River. *J. Mt. Sci.* **2004**, *22*, 179–183.
31. Guijarro, M.; Pajares, G.; Riomoros, I.; Herrera, P.J.; Burgos-Artizzu, X.P.; Ribeiro, A. Automatic segmentation of relevant textures in agricultural images. *Comput. Electron. Agric.* **2011**, *75*, 75–83. [CrossRef]
32. Yan, Y.; Wang, X.; Guo, Z. Influence of wind erosion on dry aggregate size distribution and nutrients in three steppe soils in northern China. *Catena* **2018**, *170*, 159–168. [CrossRef]
33. Yuan, J.; Fang, W.; Fan, L.; Chen, Y.; Wang, D.; Yang, Z. Soil Formation and Vegetation Establishment on the Cliff Face of Abandoned Quarries in the Early Stages of Natural Colonization. *Restor. Ecol.* **2006**, *14*, 349–356. [CrossRef]
34. Gaylarde, C.C.; Morton, L.H.G. Deteriogenic biofilms on buildings and their control: A review. *Biofouling* **1999**, *1*, 59–74. [CrossRef]
35. Aranda, S.C.; Gabriel, R.; Borges, P.A.V.; Santos, A.M.C.; Lobo, J.M. Geographical, Temporal and Environmental Determinants of Bryophyte Species Richness in the Macaronesian islands. *PLoS ONE* **2014**, *7*, e101786. [CrossRef] [PubMed]
36. Wang, M.Z.; Ye, W.; Xing, F.W. Bryophyte diversity on a tropical continental island (Hainan, China): Potential vulnerable species and environmental indicators. *J. Bryol.* **2019**, *41*, 350–360. [CrossRef]
37. Pei, J.; Ai, Y.; Liu, H.; Zhang, Z.; Zeng, L. Effects of slope posiion and aspect on vegetation restoration of excavated soil surface on Suiyu railway rock slope. *Bull. Soil Water Conserv.* **2009**, *29*, 197–201.
38. Yang, J.; Zhang, G.; Huang, L. Rock weathering and soil formation rates of a forested watershed in the typical subtropical granite Area. *Acta Pedol. Sin.* **2013**, *50*, 253–259.
39. Degu, A.M.; Hossain, F.; Niyogi, D.; Pielke, R.; Shepherd, J.M.; Voisin, N.; Chronis, T. The influence of large dams on surrounding climate and precipitation patterns. *Geophys. Res. Lett.* **2011**, *38*, 104405. [CrossRef]
40. Kumbaric, A.; Ceschin, S.; Zuccarello, V.; Caneva, G. Main ecological parameters affecting the colonization of higher plants in the biodeterioration of stone embankments of Lungotevere (Rome). *Int. Biodeterior. Biodegrad.* **2012**, *72*, 31–41. [CrossRef]
41. Downing, A.J. Distribution of Bryophytes on Limestones in Eastern Australia. *Bryolgist* **1992**, *1*, 5–14. [CrossRef]
42. Redfearn, P.L.J. The bryophyte vegetation of exposed limestone at Pronto Springs, Florida. *Rev. Bryol. Lichenol.* **1960**, 235–243.
43. Altieri, A.; Ricci, S. Calcium uptake in mosses and its role in stone biodeterioration. *Int. Biodeterior. Biodegrad.* **1997**, *40*, 201–204. [CrossRef]
44. Zhu, K. Vegetation natural recovery in Guizhou Karst Area—A case study by highway rocky slope. *J. Mt. Sci.* **2011**, *29*, 713–720.
45. Turkington, A.V.; Paradise, T.R. Sandstone weathering a century of research and innovation. *Geomorphology* **2005**, *12*, 229–253. [CrossRef]

46. Barry, R.G. *Mountain Weather and Climate*; Methuen: London, UK; New York, NY, USA, 1981; 313p.
47. Stupar, M.; Grbi, M.; Simi, G. A sub-aerial biofilms investigation and new approach in biocide application in cultural heritage conservation: Holy Virgin Church (Gradac Monastery, Serbia). *Indoor Built Environ.* **2014**, *4*, 584–593. [CrossRef]
48. Huang, Z.; Chen, J.; Ai, X.; Li, R.; Ai, Y.; Li, W. The texture, structure and nutrient availability of artificial soil on cut slopes restored with OSSS—Influence of restoration time. *J. Environ. Manag.* **2017**, *200*, 502–510. [CrossRef]
49. Bowker, M.A.; Belnap, J.; Phillips, D. Evidence for micronutrient limitation of biological soil crusts: Importance to arid-lands restoration. *Ecol. Appl.* **2005**, *15*, 1941–1951. [CrossRef]
50. Sun, S. Responses of bryophyte in alpine ecosystem to climate warming. In Proceedings of the 2012 National Symposium on Bryophyte Botany, Chengdu, China, August 2012.
51. Eldridge, J.D.; Tozer, M.E. Environment factors relating to the distribution of terricolous bryophytes and lichens semi-arid eastern Australia. *Bryologist* **1997**, *100*, 28–39. [CrossRef]
52. Sedov, S.; Zazovskaya, E.; Fedorov-Davydov, D.; Alekseeva, T. Soils of East Antarctic oasis: Interplay of organisms and mineral components at microscale. *Bol. Soc. Geológica Mex.* **2019**, *71*, 43–63. [CrossRef]
53. Turetsky, M.R.; Mack, M.C.; Hollingsworth, T.N.; Harden, J.W. The role of mosses in ecosystem succession and function in Alaska's boreal forest. *Can. J. For. Res.* **2010**, *40*, 1237–1264. [CrossRef]
54. Heimsath, A.M.; Chappell, J.; Dietrich, W.; Nishiizumi, K.; Finkel, R. Soil production on a retreating escarpment in southeastern Australia. *Geology* **2000**, *28*, 787–790. [CrossRef]
55. Singer, M.J.; Shainberg, I. Mineral soil surface crusts and wind and water erosion. *Earth Surf. Process. Landf.* **2004**, *29*, 1065–1075. [CrossRef]
56. Belnap, J.; Büdel, B.; Lange, O.L. Biological soil crusts: Characteristics and distribution. In *Biological Soil Crusts: Structure, Function, and Management*; Springer: Berlin/Heidelberg, Germany, 2001; pp. 3–30.
57. Bu, C.; Wu, S.; Xie, Y. The study of biological soil crusts: Hotspots and prospects. *Clean—Soil Air Water* **2013**, *41*, 899–906. [CrossRef]