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Revegetation of high and steep rocky slopes: Below-ground habitat reconstruction of plants

DH Su *China University of Geosciences, The People's Republic of China*

JW Zhou *China University of Geosciences, The People's Republic of China*

HB Feng *China University of Geosciences, The People's Republic of China*

Y Zhu *China University of Geosciences, The People's Republic of China*

R Li *China University of Geosciences, The People's Republic of China*

JC Ye *China University of Geosciences, The People's Republic of China*

X Han *China University of Geosciences, The People's Republic of China*

Abstract

Mining, road construction, and other engineering activities result in a huge number of high and steep rocky slopes, the ecological restoration of which is a global issue. In this study, below-ground habitat reconstruction is presented as a revegetation strategy for high and steep rocky slopes. The vegetation was established by drilling holes in the slope surface and planting appropriate arbores, shrubs, and climbing plants. Plant growth, as well as temperature and humidity dynamics on the slope, were observed over five years through planting experiments and continuous monitoring in the study area. The results indicate that the plants showed good adaptability with an overall survival rate of 77%. Moreover, Cotinus coggygria var. cinereus Engl., Parthenocissus tricuspidata (Siebold & Zucc.) Planch., Platycladus orientalis (L.) Franco, and Punica granatum Linn. had final survival rates greater than 80% and great growth rates, which could quickly establish a stable ecosystem on high and steep slopes to produce the shading effect. Therefore, they could be used as the main plants for the revegetation of high and steep rocky slopes. Simultaneously, the water vapor fields of the rocky slope were constructed for each season. The results show that the depth where the plant roots were found in the water vapor saturation zones in each season, which can generate condensation water to supply the plant growth. This research serves as a resource for revegetation and ecological restoration of high and steep rocky slopes.

Keywords: *high and steep rocky slopes, revegetation, below-ground habitat reconstruction, water vapor*

1 Introduction

Open-pit mining and the construction of infrastructure such as roads and electricity have contributed significantly to economic development and social progress, but at the same time, a large number of bare rocky slopes have been created, with serious problems of soil erosion and vegetation degradation, deteriorating the natural environment, affecting the ecological landscape of the city and reducing the quality of life of the residents (Michele & Davide 2021; Moran et al. 2014; Ramon et al. 2012). Rocky slopes make it harder to retain soil because of their steep slopes, tall heights, and smooth surfaces, which are essential for plant growth (Wang et al. 2009; Heneghan et al. 2008). Therefore, it may take up to 100 years for high and steep slopes to recover naturally, which is unacceptable for the majority of places. These factors pose a great challenge for the revegetation of high and steep rocky slopes (Duan et al. 2008).

The most common technologies for revegetation slopes, such as guest soil cover, spray seeding, three-dimensional vegetation network, etc., are designed for low and slow slopes, and their effects are frequently unsustainable when applied to high and steep slopes (Gentili et al. 2020). Although techniques such as ecological bags and step blasting can be applied to high and steep slopes, their widespread use is severely constrained by issues with difficult construction and expensive maintenance (Ursic et al. 1997; Medl et al.

2017; Clemente et al. 2004). Moreover, herbs and shrubs are the main plants currently applied, which leads to unsatisfactory results in most restoration projects due to low species diversity and simple ecosystem structure (Oliveira et al. 2011). Therefore, the current study is focused on the development of revegetation technologies appropriate to high and steep rocky slopes with sustainable effects.

To address the problems mentioned above, this study proposes an innovative method of revegetation applicable to high and steep slopes - below-ground habitat reconstruction of plants. Create below-ground habitat conditions that are suitable for plants on high and steep rocky slopes using reasonable engineering. 15 species of plants, including arbors, shrubs, and vines, were selected and planted on the restored rocky slopes so that the plants can take root and grow on the rocky slopes and absorb water and nutrients from slope fissures to achieve long-term revegetation of the high and steep slopes. This study evaluated the feasibility of the method and provided a new solution for the revegetation of high steep rocky slopes.

2 Methodology

2.1 Study area

The study area is located in the east of Jinan, the capital of Shandong Province, with latitude and longitude coordinates of 117.55°E and 36.65°N (Figure 1). It lies in the southeast of the North China Plain, with Mount Tai in the south and the Yellow River in the north (Cui et al. 2009). The topographic difference between the north and south is significant, and the geomorphic type gradually transitions from low mountains and hills in the south to alluvial plains in the north (Ci et al. 2021; Wang et al. 2015).

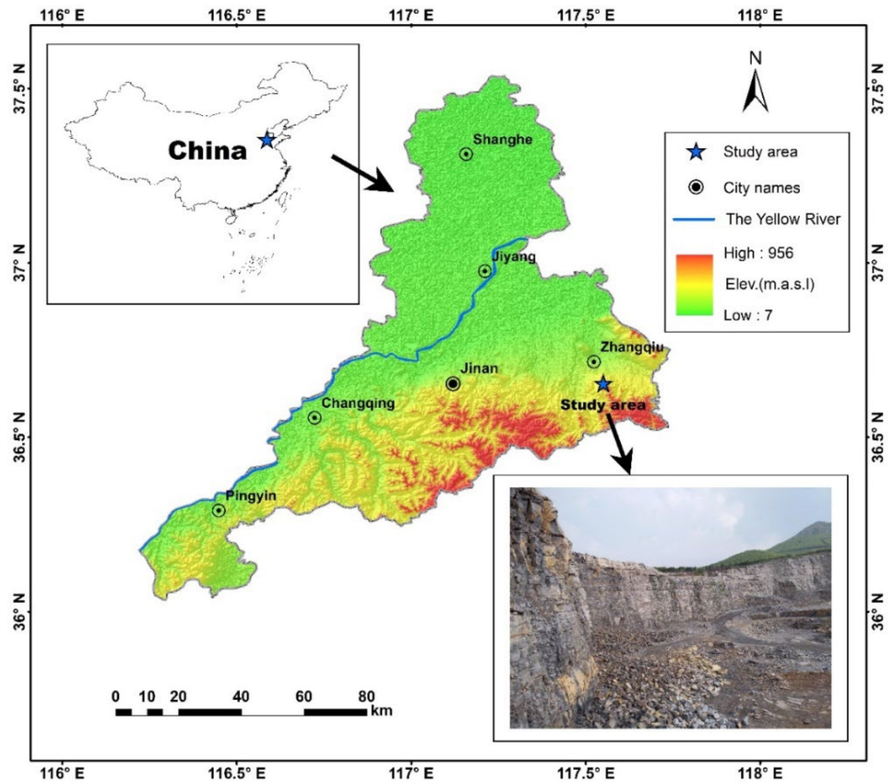

Figure 1 The study area location and overview of the rocky slope

The study area is in the mid-latitude zone, with a mild temperate continental monsoon climate affected by solar radiation, atmospheric circulation, and terrain. The climate is characterized by cold, dry winters and hot, wet summers (Yang et al. 2016). The average annual temperature is 13.8°C, and the average annual precipitation is 685 mm, with July and August accounting for about half of the precipitation (Figure 2) (Lin et al. 2014).

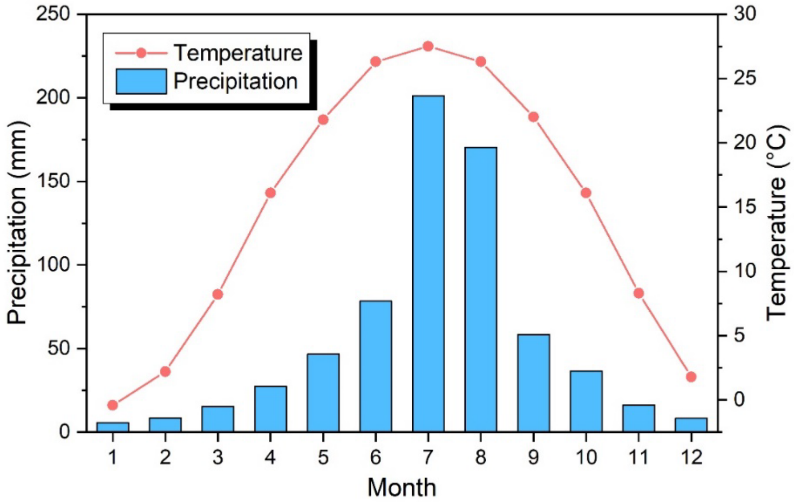

Figure 2 Multi-year monthly average temperature and precipitation of the study area

The stratum of the mountain in the study area is Ordovician dolomitic limestone, a good building stone resource. Since the 1980s, the natural landscapes and global ecosystems have been harmed due to almost a decade of heavy mining, forming a mining wasteland of around ten thousand square meters and a rock slope 10 to 50 meters high, 1 kilometer long, and slopes more than 80°. There are 5 groups of fissures in the fissured rock mass, including one group of bedding fissures and four groups of structural fissures, and the volume fissure rate is 7.32‰. In this study, a high and steep slope with a height of 20 meters and a slope of 85° was selected for the revegetation and water field monitoring experiments.

2.2 Below-ground habitat reconstruction of plants on rocky slopes

The below-ground habitat is the most critical plant habitat component, consisting of soil and the water, salinity, air, and organic matter contained therein. It is the source of water and nutrients on which plants depend for survival and growth (Feng et al. 2021).

Below-ground habitat reconstruction of plants is the artificial restoration of the below-ground habitat necessary for plant growth and survival. Create below-ground habitat conditions that are suitable for plants on high and steep rocky slopes using reasonable engineering. Suitable plants, including arbors, shrubs, and vines, are selected and planted on the restored rocky slopes so that the plants can take root and grow on the rocky slopes and absorb water and nutrients from slope fissures to achieve long-term revegetation of the high and steep slopes. The following main points can be summarized.

2.2.1 Investigation of below-ground habitat structure of native plants

The quadrat method was utilized to investigate the dominant plant species around the high and steep slopes. Then, sample pits were excavated within the quadrats for the investigation of the below-ground habitat structure of plants. The specifications of the sample pits are shown in Figure 3. Use nails and nylon cord to divide the investigation surface into 10 × 10 small squares of size 10 cm × 10 cm. Counting the number of coarse (root diameter ≥ 10 mm), medium (10 mm > root diameter > 2 mm), and fine (root diameter ≤ 2 mm) roots in each square, analyzing the frequency of the three kinds of roots at various depths, and determining the position of the plant root mass (it's part of the root system that has the most amounts of root hairs and it is the functional zone for water and nutrient absorption) in the depth range between 20% and 80% of the cumulative frequency. Soil samples were taken at each layer and tested for available phosphorus, rapidly available potassium, and alkaline hydrolysis nitrogen. The investigation can serve as a foundation for the selection of plants and the construction of the habitat structure.

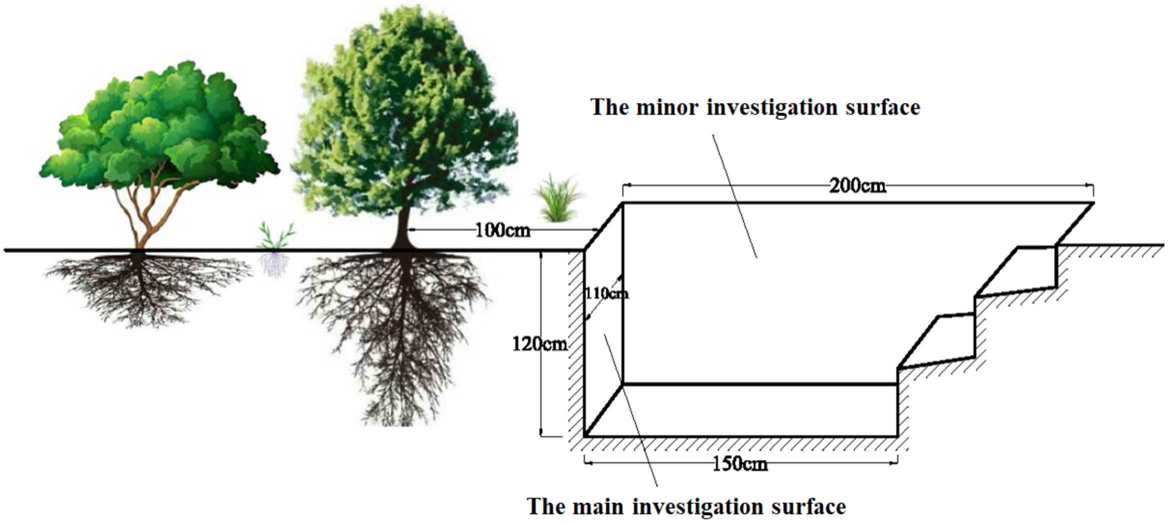

Figure 3 Sample pits for investigating the underground habitat structure of plants

2.3 Data collection

2.3.1 Plant survival and growth monitoring

The survival rate and growth indicators including apical height, base diameter, and crown diameter of the 15 plants were investigated at 3 months (August 2015), 2 years (August 2017), 3 years (August 2018), 4 years (August 2019) and 5 years (August 2020) after planting. Growth indicators were investigated using a random sampling method with a 15% probability of sampling.

The annual growth rate (AGR) was calculated using the following equation:

$$AGR\% = \frac{N_j - N_i}{N_i \Delta T} \times 100 \tag{1}$$

where:

N_i = the value of the indicator for the last measurement, N_j = the value for the next measurement, ΔT = the number of year past between the measurements.

2.3.2 Slope water vapor field monitoring

We conducted monitoring experiments to study the distribution and transformation characteristics of the water vapor field. Three horizontal monitoring holes were arranged on the rocky slope, which were 2 m, 10 m, and 18 m away from the ground respectively (Figure 4). The diameter of the monitoring holes was 10 cm, and the depth was 200 cm.

The temperature and humidity monitors (iButton DS1923, Maxim Integrated Ltd., San Jose, CA, USA) with automatic recording and storage functions were fixed on a PVC tube and placed at different depths (0 cm, 10 cm, 20 cm, 40 cm, 60 cm, 100 cm, 150 cm, and 200 cm) of the monitoring holes (Figure 4). The monitoring holes were blocked by sealing plugs to ensure the accuracy of the monitoring results.

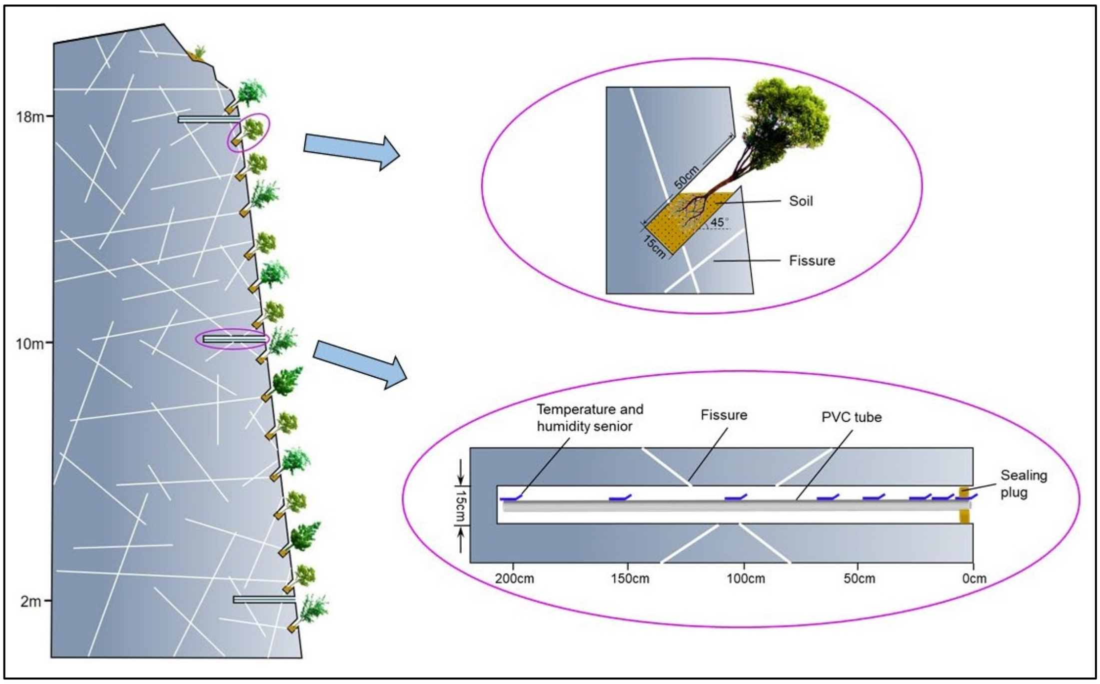

Figure 4 The arrangement of monitoring holes on the rock slope and the placement of monitors in the monitoring holes

The experiments were conducted in four seasons of a hydrological year: summer (July 14th to July 21st, 2018), autumn (October 27th to November 4th, 2018), winter (January 10th to January 17th, 2019), and spring (April 23rd to 30th, 2019). Uninterrupted data collection was carried out during each monitoring period. The monitoring frequency was every 10 min. The experiments collected more than 80,000 sets of temperature and humidity data.

2.3.3 Design of drilling holes and determination of holes position

The fissures serve as a channel for plants to obtain water and nutrients as well as a place for plant roots to develop. Therefore, the fissures played a significant role in determining the location of the planting hole, with its density and size serving as the primary indicators. The planting holes had a diameter of 15 cm, a depth of 50 cm, and a downward sloping angle of 45° (Figure 4). The horizontal and vertical distance between the planting holes was 1 m.

2.3.4 Plant species selection

The selection of plant species was guided by the following principles: a) Mainly native plants; b) Plants with strong tolerance to drought and infertile properties; c) Plants with Strong sprouting of roots; d) A variety of arbors, shrubs, and vines to ensure ecosystem stability; e) Plants with ornamental properties.

15 plants were selected for this study, and the plant species and numbers are shown in Table 1.

Table 1 Plant species and numbers

No.	Species	Family	Growth form	Leaf habit	Numbers	Proportion/%
1	*Cotinus coggygria var. cinereus* Engl.	Anacardiaceae	Arbor	Deciduous	577	60.80
2	*Forsythia suspensa* (Thunb.) Vahl	Oleaceae	Shrub	Deciduous	193	20.34
3	*Parthenocissus tricuspidata*	Vitaceae	Vine	Deciduous	20	2.11

	(Siebold & Zucc.) Planch.					
4	*Campsis grandiflora* (Thunb.) Schum.	Bignoniaceae	Vine	Deciduous	17	1.79
5	*Wisteria sinensis* (Sims) Sweet	Papilionaceae	Vine	Deciduous	18	1.90
6	*Platycladus orientalis* (L.) Franco	Cupressaceae	Arbor	Evergreen	20	2.11
7	*Euonymus fortunei* (Turcz.) Hand.-Mazz.	Celastraceae	Vine	Deciduous	20	2.11
8	*Chimonanthus praecox* (Linn.) Link	Calycanthaceae	Arbor	Deciduous	10	1.05
9	*Syringa oblata* Lindl.	Oleaceae	Arbor	Deciduous	15	1.58
10	*Pinus bungeana* Zucc. ex Endl.	Pinaceae	Arbor	Evergreen	15	1.58
11	*Robinia pseudoacacia* Linn.	Papilionaceae	Arbor	Deciduous	10	1.05
12	*Pinus thunbergii* Parl.	Pinaceae	Arbor	Evergreen	10	1.05
13	*Lonicera japonica* Thunb.	Caprifoliaceae	Vine	Deciduous	8	0.84
14	*Punica granatum* Linn.	Punicaceae	Arbor	Deciduous	8	0.84
15	*Armeniaca sibirica* (Linn.) Lam.	Rosaceae	Arbor	Deciduous	8	0.84
	Total				949	100

2.3.5 Planting hole water conductivity test

Density and size can only describe the apparent characteristics of the fissures, but not the connectivity of the fissures. Excellent connectivity provides plants with adequate oxygen, water, and nutrients. The connectivity of fissures can be obtained by hydraulic conductivity tests.

Water was injected into the planting hole and the change in water level over time was observed to determine the good or bad hydraulic conductivity. Depending on the rate of water level drop, the hydraulic conductivity of the planting holes was classified into three levels: a) The water level dropped more than 5cm within 1 minute, the hydraulic conductivity was good; b) Water level dropped more than 1cm less than 5cm within 1 minute, the hydraulic conductivity was medium; c) Water level drops less than 1cm within 1 minute, the hydraulic conductivity is poor, and the planting holes of this level were discarded.

2.3.6 Plants transplanting

After completing the above, the mixture of soil and organic fertilizer was filled into the planting holes, which provided initial nutrition for plants. Then, the plant seedlings were transplanted and each plant was numbered to create its growth profile.

3 Results and discussion

3.1 Plant survival rate

In 2015, we planted 949 plants by drilling holes in the rocky slope and carried out monitoring experiments on plant survival rates. As shown in Figure 5, the plant survival rate of the rocky slope gradually declined and stabilized with time. In 2020, the survival rate was 76.92%, indicating that the plants have adapted to the harsh habitat of the rocky slope. Meanwhile, we mulched the summit of the rocky slope with 40 cm of soil and planted dozens of plants of the same species and size, but after three months, every plant perished. Additionally, in 2016, the local government conducted ecological restoration work for the quarry by mulching 80 cm of soil at the foot of the rocky slope and planting 126 plants, including *P. orientalis* (L.) Franco and *Prunus cerasifera* 'Pissardii', only nine of which survived a year later. The government realized that the restoration was not effective, so 307 additional plants were replanted at the foot of the rocky slope. The survival rate of plants decreased rapidly to 25.95% in the first year, and then slowly declined and stabilized.

The results above demonstrated that the survival rate of plants growing on rock walls was significantly higher than that of plants growing in mulch, contrary to what we typically consider soil is a better habitat for plants than rock. We believe there are two reasons for this: On the one hand, the soil exchanges moisture with the atmosphere more intimately due to its higher porosity than the fissure rate of the rock mass. The water holding capacity is weak when the surface lacks coverage with vegetation; On the other hand, the specific surface area of soil is significantly larger than that of rock mass, leading to greater matrix suction of soil than fissures. It is more difficult for plants to absorb water from the soil under the same circumstances. This further confirms the significance of the water vapor field of the rocky slope in supplying the water required for plant growth.

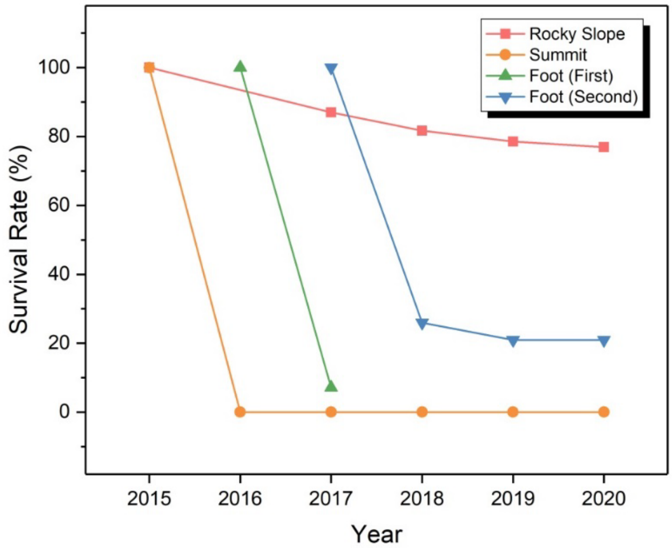

Figure 5 Survival rate of plants on rocky slope compared to those planted at the summit and foot from 2015 to 2020

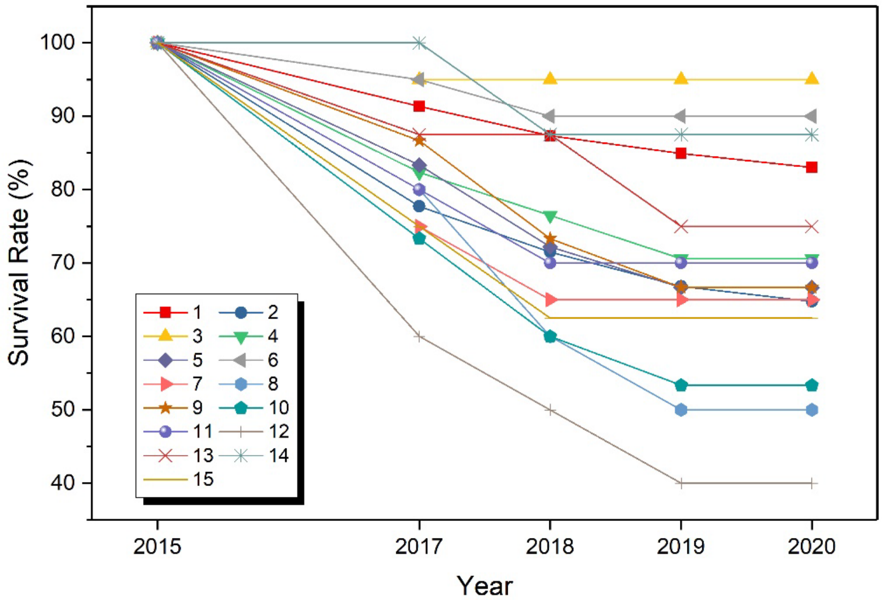

Figure 6 Variation of survival rate of different plants for rocky slope revegetation from 2015 to 2020

Figure 6 illustrates the variation in the survival rates of the 15 plant species in Table 1 over 5 years. During the first two months after planting, we maintained the plants with irrigation to prevent them from dying in the early stages when they were not adapted to the extreme conditions of the rocky slopes. As a result, the survival rate of all species was 100% after 3 months of planting. Two years after planting, the survival rate of the plants all decreased. The survival rates of *P. granatum* Linn., *P. orientalis* (L.) Franco, *P. tricuspidata* (Siebold & Zucc.) Planch., and *C. coggygria var. cinereus* Engl. were all above 90%. While the survival rates of

P. bungeana Zucc. ex Endl. and *P. thunbergii* Parl. were lower, both below 75%. After three years of planting, the decline in the survival rate of most plants slowed down and basically reached stability after four years of planting, indicating that the plants have adapted to the harsh habitat of the slope. Overall, the survival rates of *C. coggygria var. cinereus* Engl., *P. tricuspidata* (Siebold & Zucc.) Planch., *P. orientalis* (L.) Franco and *P. granatum* Linn. were greater than 80% after five years, showing that they were excellent candidates for revegetation of high and steep slopes.

Figure 7 Comparison of the high and steep slope revegetation before (2014) and after (2019)

3.2 Plant growth indicators

Apical height, base diameter, and crown diameter play an important role in indicating the growth status of plants. Apical height (AH) is the distance from the soil of the hole to the apical bud of the plant. Base diameter (BD) is the diameter of the main stem of the plant at the soil surface. Crown diameter (CD) is the mean of the lengths of the long and short axes of the crown. Table 2 shows the BD, AH, CD, and their annual growth rates (AGR) of plants on the slope monitored during 2015-2020.

Table 2 Plant growth from 2015 to 2020

Species	Time	BD/cm	AGR/%	AH/cm	AGR/%	CD/cm	AGR/%
C. coggygria var. cinereus Engl.	2015.08	0.86	52.63	53.28	196.81	33.58	742.18
	2017.08	1.72	50.00	84.58	29.37	69.85	54.01
	2018.08	2.16	25.58	96.09	13.61	87.34	25.04
	2019.08	2.64	22.22	110.16	14.64	109.32	25.17
	2020.08	3.13	18.56	130.17	18.16	132.76	21.44
F. suspensa (Thunb.) Vahl	2015.08	0.75	10.96	40.38	26.17	24.36	36.56
	2017.08	1.06	20.67	59.45	23.61	47.32	47.13
	2018.08	1.25	17.92	66.00	11.02	57.14	20.75
	2019.08	1.42	13.60	72.24	9.45	63.33	10.83
	2020.08	1.71	20.42	79.85	10.53	71.85	13.45
P. tricuspidata (Siebold & Zucc.) Planch.	2015.08	0.37	148.15	17.38	305.07	8.80	47.84
	2017.08	1.00	85.14	131.00	326.87	16.67	44.72
	2018.08	1.70	70.00	141.33	7.89	24.00	43.97
	2019.08	2.40	41.18	153.33	8.49	32.33	34.71
	2020.08	3.20	33.33	168.00	9.57	42.33	30.93
C. grandiflora (Thunb.) Schum.	2015.08	0.71	125.93	29.37	59.44	13.00	18.34
	2017.08	0.90	13.38	49.78	34.75	19.67	25.65
	2018.08	1.06	17.78	65.22	31.02	28.33	44.03

	2019.08	1.27	19.81	83.11	27.43	36.67	29.44
	2020.08	1.49	17.32	103.56	24.61	46.67	27.27
***W. sinensis* (Sims) Sweet**	2015.08	0.73	29.41	50.50	102.49	30.83	109.59
	2017.08	1.60	59.59	97.50	46.53	96.00	105.69
	2018.08	2.00	25.00	110.50	13.33	109.50	14.06
	2019.08	2.55	27.50	125.50	13.57	124.50	13.70
	2020.08	3.20	25.49	143.50	14.34	143.50	15.26
***P. orientalis* (L.) Franco**	2015.08	0.84	80.00	44.73	112.52	21.82	196.17
	2017.08	1.96	66.67	79.45	38.81	29.18	16.87
	2018.08	2.34	19.39	86.64	9.05	35.64	22.14
	2019.08	2.89	23.50	96.82	11.75	42.82	20.15
	2020.08	3.41	17.99	109.82	13.43	52.82	23.35
***E. fortunei* (Turcz.) Hand.-Mazz.**	2015.08	0.35	66.67	25.25	993.10	28.92	651.64
	2017.08	0.75	57.14	78.83	106.10	55.83	46.52
	2018.08	1.16	54.67	87.40	10.87	67.00	20.01
	2019.08	1.66	43.10	95.00	8.70	75.00	11.94
	2020.08	2.40	44.58	104.40	9.89	84.60	12.80
***P. bungeana* Zucc. ex Endl.**	2015.08	0.88	19.05	24.33	17.15	21.50	44.90
	2017.08	1.28	22.73	29.12	9.84	32.00	24.42
	2018.08	1.54	20.31	32.00	9.89	37.00	15.63
	2019.08	1.82	18.18	40.00	25.00	42.00	13.51
	2020.08	2.13	17.03	60.00	50.00	50.00	19.05
***R. pseudoacacia* Linn.**	2015.08	0.76	67.69	44.25	274.29	37.75	623.73
	2017.08	3.00	147.37	120.00	85.59	160.00	161.92
	2018.08	5.00	66.67	137.00	14.17	166.00	3.75
	2019.08	6.00	20.00	151.00	10.22	173.00	4.22
	2020.08	6.90	15.00	163.00	7.95	182.00	5.20

The plants in the table all showed significant increases in BD, AH, and CD, demonstrating that the revegetation plants on the slope have been well adapted. The annual growth rates of all growth indicators increased rapidly at the early stage and gradually decreased and stabilized with time. It has been shown that some woody plants allocate more resources to the root system and less to the above-ground parts in drought conditions as a way to increase water uptake and promote plant growth (Eunice et al. 2007; Peter et al. 2006). Thus, the growth of plant BD reflected the development of a large root network. The BD of vines (*P. tricuspidata* (Siebold & Zucc.) Planch. and *C. grandiflora* (Thunb.) Schum.) grew fastest three months after planting, with annual growth rates exceeding 100%, followed by arbors (*C. coggygria var. cinereus* Engl., *P. orientalis* (L.) Franco and *R. pseudoacacia* Linn.), with annual growth rates exceeding 50%, and *F. suspensa* (Thunb.) Vahl and *P. bungeana* Zucc. ex Endl., with annual growth rates below 20%. After that, the BD of *C. coggygria var. cinereus* Engl., *P. tricuspidata* (Siebold & Zucc.) Planch., *R. pseudoacacia* Linn., and *P. orientalis* (L.) Franco still showed faster growth rates. Similarly, most of the vines and arbors had faster growth rates three months after planting, all exceeding 100%, with *W. sinensis* (Sims) Sweet even reaching 993.10%, while the annual growth rates of *C. grandiflora* (Thunb.) Schum. and *P. bungeana* Zucc. ex Endl. AH were only below 30%, indicating slow growth. The size of the crown width indicated the shading effect of the plants on high and steep slope. Arbors grew rapidly in the early stages of the forest canopy. Three months after planting, the annual crown diameter growth rates of *C. coggygria var. cinereus* Engl. and *R. pseudoacacia* Linn. were above 600%, whereas those of *F. suspensa* (Thunb.) Vahl, *C. grandiflora* (Thunb.) Schum., and *P. bungeana* Zucc. ex

Endl. were all under 50%. Since *P. tricuspidata* (Siebold & Zucc.) Planch. grew mainly vertically, the canopy width did not increase rapidly, but its growth rate was stable.

Overall, species with good growth status and rapid growth rates, such as *C. coggygria var.* cinereus Engl., *P. orientalis* (L.) Franco, *R. pseudoacacia* Linn., and *P. tricuspidata* (Siebold & Zucc.) Planch., can quickly establish a stable ecosystem on high and steep slopes to produce the shading effect. These species could be used as the main plants planted on high and steep rocky slopes. In contrast, the growth of *P. bungeana* Zucc. ex Endl., *F. suspensa* (Thunb.) Vahl and *C. grandiflora* (Thunb.) Schum. was general, indicating that they may not be suitable for planting on high and steep side slopes.

Figure 8 **Growth of revegetation plants on the high and steep rocky slope in 2019. (a) *C. coggygria var. cinereus* Engl.; (b) Side view of slope; (c) *R. pseudoacacia* Linn.; (d) *C. coggygria var. cinereus* Engl.; (e) *P. tricuspidata* (Siebold & Zucc.) Planch.**

3.3 Slope water vapor field

Figure 9 depicts the seasonal distribution of water vapor partial pressure in the rocky slope, enabling the analysis of the seasonal characteristics of water vapor migration. The water vapor partial pressure and water vapor partial pressure gradient were highest in summer and lowest in winter and between summer and winter in autumn and spring. The high temperature and precipitation in the study area during the summer and spring resulted in high water vapor content and water vapor partial pressure in the air, so the atmosphere became a source of water vapor for the rocky slope, and the water vapor partial pressure decreased from the shallow to the deep part of the rocky slope, which was consistent with the direction of water vapor migration.

The air was cold and dry resulting in a low temperature and water vapor concentration in winter and autumn. While the groundwater saturated zones had a greater temperature than the unsaturated zones, where the liquid water vaporized quickly and had higher water vapor content, it became a source of water vapor for the unsaturated zones. Water vapor migrated from the deep to the shallow part of the rocky slope as its partial pressure decreased.

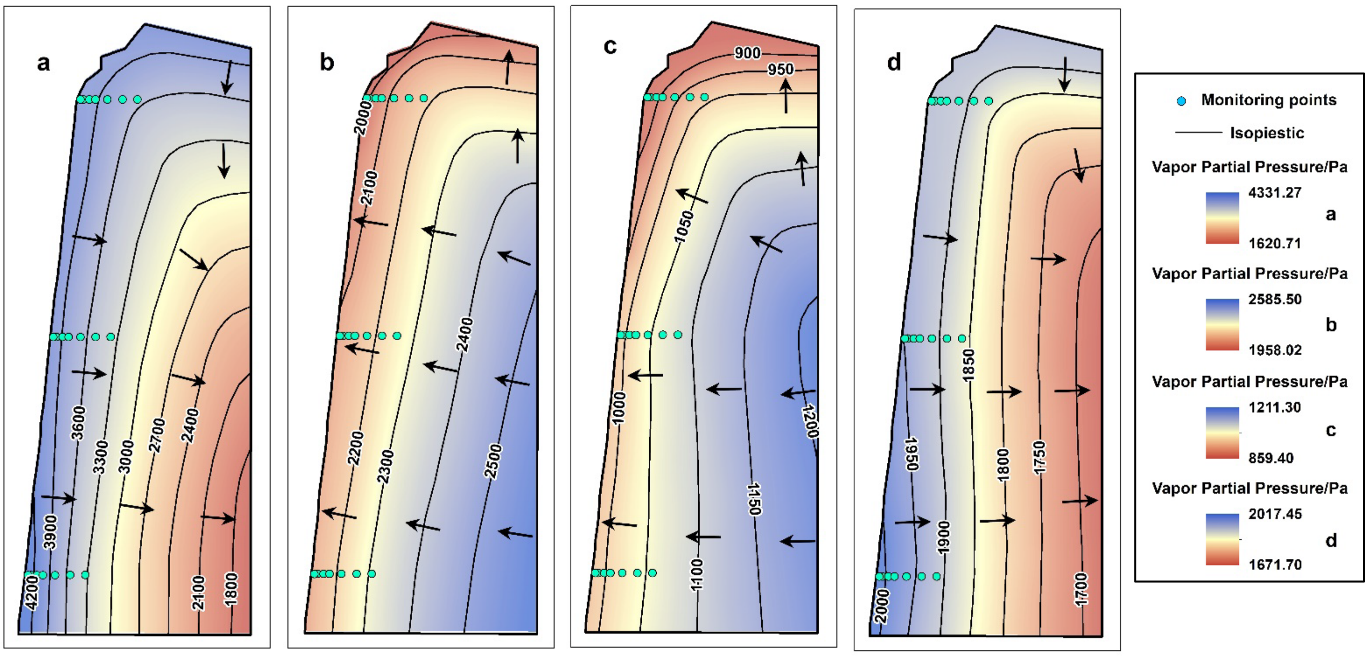

Figure 9 The rocky slope water vapor partial pressure contour maps in different seasons. (a) Summer; (b) Autumn; (c) Winter; (d) Spring

Figure 10 illustrates the seasonal distribution of water vapor saturation zones in the rocky slope. Summer and spring water vapor saturation zones were similar in extent and more widely distributed. It extended from 100 cm to the deep part of the rocky slope in summer and from 40 cm to the deep in spring. Water vapor saturation zones were equally approximated in autumn and winter but significantly different from summer and spring, with substantial shrinkage occurring. It ranged from 20 cm to 60 cm, with a somewhat greater bottom range of up to 100 cm; and the range was from 10 cm to 100 cm in the winter.

Condensate is generated in the water vapor saturation zones when the rate of condensation of vapor exceeds the rate of evaporation of water. The formation of condensate, according to Wang et al. (2022), can be divided into three stages: the first stage involves the generation of droplets on the fissure surface; the second stage involves the coalescence of droplets when the number of droplets is great; and the third stage involves the coalescent droplets connecting to form a water film as the number of droplets continues to rise. The plant roots that grew into the fissures could absorb the condensate there, supplying the growth and development of the rocky slope plants. Water vapor saturation zones were generated in the rocky slope at the positions of plant roots in the autumn, winter, and spring; even though the range of the saturation zone began at 100 cm in the summer, it was also produced at shallow depths at night. Therefore, rocky slope plants can obtain water from the fissured rock slope in different seasons.

Furthermore, the fissures returned to the unsaturated state of water vapor when the plants absorbed the condensate in them, and the surrounding water vapor would be transported to the regions under the gradient of water vapor partial pressure, causing the fissures to reach the saturated state of water vapor again and continue to produce condensate. As a result, the fissure network functions as a sustained system of water supply pipelines, continuously supplying water to the plants.

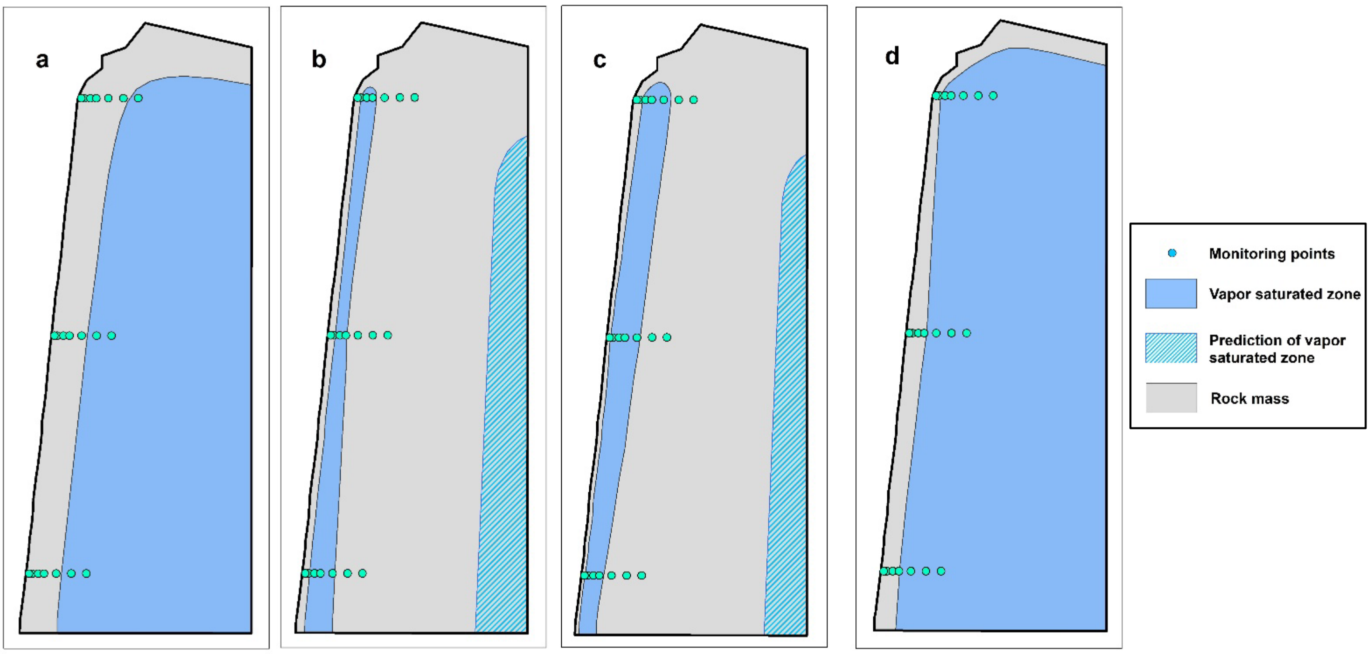

Figure 10 The distribution of water vapor saturation zones in different seasons. (a) Summer; (b) Autumn; (c) Winter; (d) Spring

4 Conclusion

In this study, 15 plant species, including arbors, shrubs, and vines, were selected to revegetate the high and steep rocky slopes by using below-ground habitat reconstruction of plants. By conducting a 5-year-long monitoring experiment on the survival rate and growth of revegetation plants as well as the water vapor field monitoring experiments on rocky slopes, the effect of revegetation of high steep rocky slopes and the water source of plants were studied. The following main points can be summarized.

(1) After 5 years of planting, the survival rate of high steep rocky slope revegetation plants was 77%, indicating that the plants have adapted to the harsh habitat on the high steep rocky slope. *C. coggygria var. cinereus* Engl., *P. tricuspidata* (Siebold & Zucc.) Planch., *P. orientalis* (L.) Franco, and *P. granatum* Linn. had final survival rates greater than 80% and could be used as the main plants for revegetation of high and steep rocky slopes.

(2) Species with good growth status and rapid growth rates, such as *C. coggygria var.* cinereus Engl., *P. orientalis* (L.) Franco, *R. pseudoacacia* Linn., and *P. tricuspidata* (Siebold & Zucc.) Planch., can quickly establish a stable ecosystem on high and steep slopes to produce the shading effect. These species could be used as the main plants planted on high and steep rocky slopes. In contrast, the growth of *P. bungeana* Zucc. ex Endl., *F. suspensa* (Thunb.) Vahl and *C. grandiflora* (Thunb.) Schum. was general, indicating that they may not be suitable for planting on high and steep rocky slopes.

(3) Water vapor saturation zones were generated in the rocky slope at the positions of plant roots in every season, where condensate was generated. Therefore, rocky slope plants can obtain water from the fissured rock slope in different seasons, and the fissure network functions as a sustained system of water supply pipelines, continuously supplying water to the plants.

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