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Original Article **Special Topic on Ecological Assets and Ecosystem Services in the Qinghai-Tibet Plateau**

Evaluating the success of engineering disturbed slope eco-restoration in the alpine region, southeast Qinghai-Tibet Plateau, China

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Abstract: Slope eco-restoration has always received extensive attention as a positive way to reverse ecosystem deterioration derived from human interventions. A simplified framework is proposed to undertake a quantitative evaluation of the engineering disturbed slope eco-restoration success in the alpine region, southeast Qinghai-Tibet Plateau. The Dagu hydropower project that disturbs the local ecosystem to some certain was selected as the study area. Since August 2018, six types of slope (soil, rock, soil-rock, spoil, construction site, hardened) were served as the demonstration test for the slope eco-restoration with two years monitoring in the study area. Meanwhile, the topography, erosion, soil quality, and vegetation were selected as assessment indicators of the methodology. Finally, combined with the weighting method and the expert panel, the slope eco-restoration quality index (SERQI) was established and applied in the six slopes. The results suggested that the frost-resistant ecological substrate performed well in alpine region, and the SERQI value is in accordance with the actual monitoring level with spoil slope>soil slope>construction site slope>soil-rock slope>rock slope>hardened slope. The proposed framework could support slope eco-restoration practitioners for making a more objective and quantitative evaluation easily for the post-implementation restoration.

Keywords: Slope eco-restoration; Restoration evaluation; Ecological indicator; Hydropower station; Qinghai-Tibetan Plateau.

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1 Introduction

Southwestern China, including Qinghai-Tibet plateau, Yunnan-Kweichow plateau, etc., is rich in hydropower resources, creating favorable conditions for the comprehensive development of hydropower (Wang 2017). As a critical ecologically fragile area (Huang 2002; Liu et al. 2019), large number of construction measures would disturb the original slope ecosystem functions (Bochet and García-Fayos 2004; Li et al. 2015), like soil erosion, vegetation degradation, water conservation and stability decline. Unlike the earthquake or landslide that could foster the evolution of slope landscapes as part of their self-regulating capacity (Gonzalez-Ollauri and Mickovski 2017), the engineering construction will leave a permanent wound for the slope ecosystem in mountainous regions (Yang et al. 2018). The problem of the slope ecosystems that cannot self-restoring caused by hydropower projection construction, especially in Qinghai-Tibet plateau, have received increasing attention worldwide (Xue et al. 2018; Zhen et al. 2018). Based on this, the artificial slope eco-restoration technology, considering slope reinforcement and vegetation reconstruction, is blowout development (Zhao et al. 2016). The technology is often ahead of theoretical research, and the vegetation in the alpine region with short growing seasons making its hard to judge whether the slope eco-restoration is well or not (Campbell and Bergeron 2012; Zhao et al. 2016). Hence, there is an urgent need to develop effective approach to assess the artificial slope eco-restoration in the alpine region (Williams 2011; Chen et al. 2017) in term of the cost-efficiency and effects.

Evaluating the engineering disturbed slope eco-restoration is not straightforward, with extensive debates surrounding how to propose an objective framework and how best to quantitative measure it. Hobbs and Norton (1996) defined that an objective framework should include the aims and the methodologies. During the last decade's debates, scientists argued that the framework needs to look beyond ecology and include the influence of climate change and socioeconomic circumstances (Higgs 1997; Seabrook et al. 2011; Le et al. 2012). The aims of engineering disturbed eco-restoration success are to repair multiple facets of a damaged ecosystem, including its composition, structure, and function. Based on this, many assessment methods of slope eco-restoration success have been developed, like empirical assessment, long-term monitoring, conceptual framework, attributes and indicators analysis (Hobbs and Norton 1996; Nilsson et al. 2016; Beier et al. 2017). The latter two methods are so-called index approaches using the objective facts instead of subjective judgments. Many assessment literatures of slope eco-restoration indicate that index method have not systematically examined the evaluation method for the specific restoration (artificial restoration technology) (Huang et al. 2018; Zhen et al. 2018), although these methods are properly described and justified. Yang et al. (2019) synthesized critical attributes from large of data to choose objective indicators based on fuzzy AHP model to evaluate the quarry slopes in Wuhan City, and the quantitative method could comprehensively reflect the effect of eco-restoration success (Wilker et al. 2016). In contrast, the empirical methods require much less data based on the empirical-statistical relationships (Wortley et al. 2013), but they do not take the socioeconomic circumstances and other influences into account (Gatica-Saavedra et al. 2017). The long-term monitoring of post-implementation restoration is widely used to evaluate engineering disturbed eco-restoration success, and such approach has often been restricted to a single or a few events and consuming a lot of time (Zedler and Callaway 2000; Hagen and Evju 2013).

In the Yarlung Tsangpo River of Qinghai-Tibet Plateau area, a hydropower station of Dagu (DG) has been constructed from 2015 to 2022 with a total capacity of 660 MW (higher than the Zangmu Hydropower Station, https://en.wikipedia.org/wiki/Zangmu_Dam). Hydropower development often causes strong disturbances to the local ecological system (Li et al. 2015). For example, the construction activities during the construction of hydropower station will directly destroy the original surface vegetation, reducing the soil anti-erosion ability and easily causing soil erosion. At the same time, the natural stability of the exposed surface and high-steep slope was damaged due to the engineering excavation, which was prone to the phenomenon of erosion and collapse. In addition, if no protective measures are taken for the spoil slope produced by the engineering construction, and the surface of the spoil slope will not be covered by vegetation for a long time, it will cause slope collapse under the erosion of rainwater. Hence, China Three Gorges University has launched six different demonstration tests of engineering disturbed slopes in this hydropower disturbance area to prepare for ecological restoration in high latitude and high elevation areas. Sun and Peng (2014) implied that different region and eco-restoration type should be combined with local conditions to establish different evaluation indicators, otherwise the judgment of the result will not accurate. Equally as important, Gatica-Saavedra et al. (2017) announced the indicators of responses to management should be tailored specifically to the type of ecosystem being restored, especially the artificial vegetation restoration in high latitude and high elevation (Campbell and Bergeron 2012). In addition, the large temperature difference and short growing seasons in special region of Qinghai-Tibet Plateau area were not considered in the common indicators (Huang et al. 2018). For these reasons, this paper aims to establish a simplified framework for quantitatively assessing the effects of hydropower project disturbed slope eco-restoration in the alpine region, bridging the gap between scientific knowledge and practical needs.

2 Study Area

2.1 Overview of Dagu (DG) hydropower project area

The DG hydropower station is located in the transition zone of the southeast edge of the Qinghai-Tibet Plateau (Fig. 1A), and is the second cascade hydropower station at the middle reach of the Yarlung Tsangpo River. The drainage area controlled by the station is nearly 15.74×10^4 km^2 with a length of 49 km main stem and 282 m river fall along the Yarlung Tsangpo River. The elevation at the station is around 3400 m above sea level (a.s.l) with the gradient of about 5.75‰, the valley width here is around 40~200 m, and the elevation on its both banks are over 6000 m a.s.l. (Fig. 1B). Moreover, the characteristic of landform is a typical high mountain and deep valley at

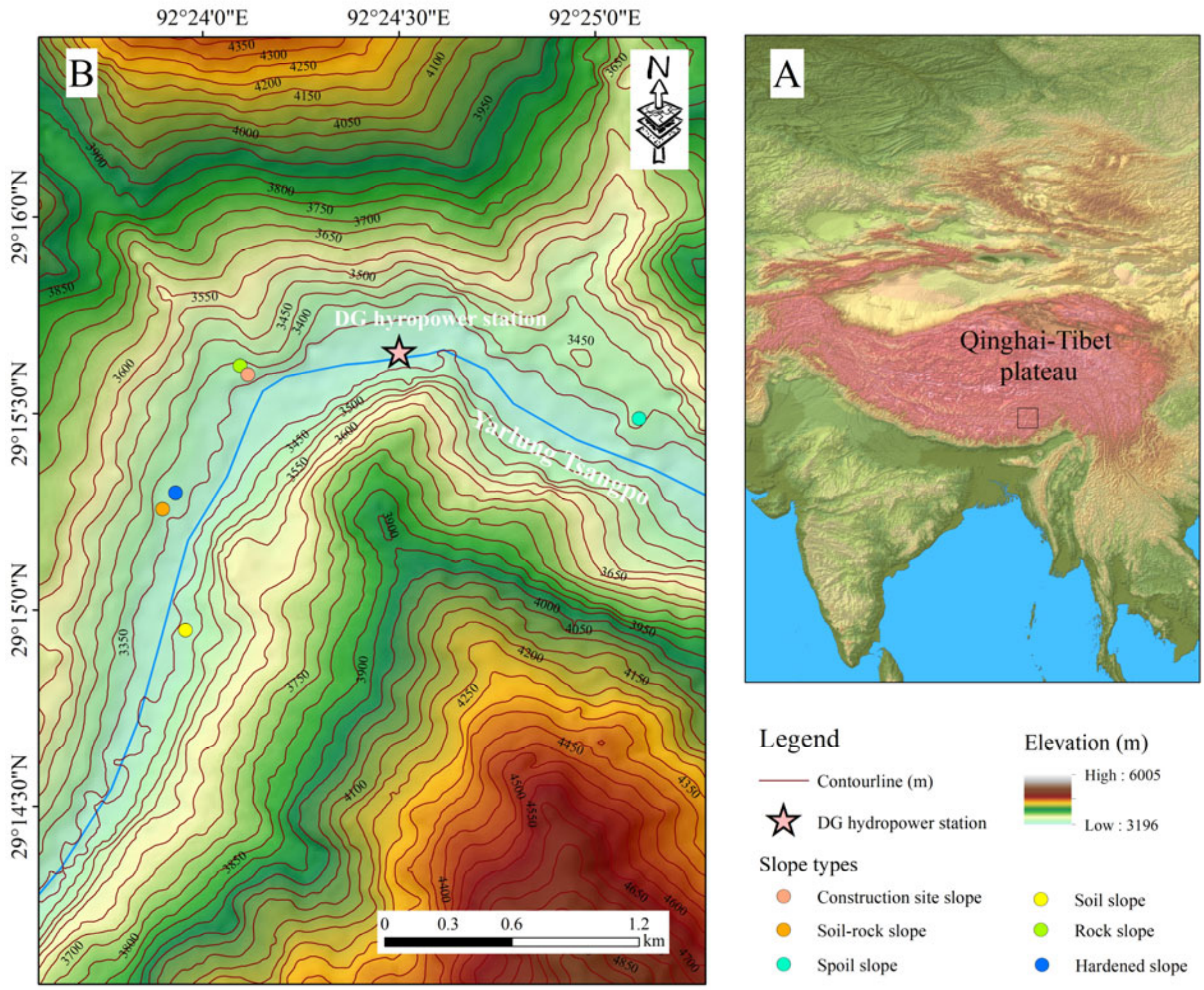

Fig. 1 Geomorphological settings of the study area. A- Location of study area; B- showing the elevation distribution of different slopes and the location of DG hydropower station; the based map with spatial resolution of 12.5×12.5 m was ALOS PALSAR DEM that downloaded from ASF Data Research (2020).

study area. The regional climate belongs to the plateau temperate monsoon semi-humid climate zone leading to little rainfall and drought in the winter and abundant precipitation in the summer. According to the statistics data from Gyaca Meteorological Station (Zeng 2015), the annual average temperature, precipitation, evaporation, and relative humidity are 9.2°C, 540.5 mm, 2084.1 mm, and 51%, respectively, and the maximum frozen soil depth over the years is approximately 19 cm. The main types of soil in the project area are grassland soil, aeolian soil, skeletal soil, etc., of which grassland soil is dominant soil that composed by loam in the project area. In addition, the lithology of the exposed rock is mainly biotite granodiorite with a medium-fine-grained structure, which can be used as an aggregate source for slope ecological restoration projects.

2.2 Slope ecological restoration

According to the engineering characteristics of the DG hydropower station, six types of slopes are selected including soil, rock, soil-rock, spoil, construction site, and hardened slopes (Fig. 1), as demonstration test for cut slope revegetation. The aspect of each slope is 289°, 108°, 126°, 263°, 106°, and 147°, respectively, and the gradient of them is 40°, 30°, 46°, 25°, 10°, and 35°, respectively. Among many slope eco-restoration technologies, like CBS (Concretes biotechnical slope), TBS (Thick layer base slope), PEB (Preventing erosion basic-material) (Zhao et al. 2016), a patent of frost-resistant ecological substrate that invented by Zhou et al. (2016) was adopted to conduct the demonstration test from July to August, 2018. The frost-resistant ecological substrate prepared from soil, concrete, quick-release fertilizer, organic material, frost-resistant additive, and water in a certain proportion. The artificial substrate has both physical and mechanical properties of soil and cement, such as scour resistance, stability, and frost-resistance, that can withstand several freeze-thaw cycles without being destroyed and its strength does not decrease seriously (Gao et al. 2020). The method of mechanical dry spraying was used in the demonstration test, because the method is appropriate for the small cut slope (Xu et al. 2012). In addition, the substrate is divided into two layers, one is the basic layer providing the vegetation growth environment, and the other is the surface layer mixed with seeds. Each slope used the equal amount of evenly mixed pioneer species of *Poa annua* L., *Festuca rubra* L., *Elymus dahuricus* Turcz., and *Medicago sativa* L.. These vegetation species are selected because they are commonly used frost-resistant plants in alpine slope region. In accordance with the surface slope exposed feature, the average thickness of surface layer is set uniformly to 2 cm, but average thickness of basic layers is set as 8 cm (soil slope), 10 cm (rock slope), 18 cm (soil-rock slope), 8 cm (spoil slope), 20 cm (construction site slope), and 13 cm (hardened slope), respectively. Due to the different surface slope exposed feature, the thickness of soil base material layer required by various slopes is different. According to the previous research and slope repair technology (Xu et al. 2012; Zhao et al. 2017), the thickness of the six kinds of slope is reasonable in the demonstration tests. After the slope eco-restoration in the DG hydropower project area, we conducted monitoring for nearly two years, and the following pictures shows the comparison pre- and post-implementation restoration (Fig. 2). In previous studies (Xin 2017; Yang et al. 2016), the monitoring time for the effect of slope ecological restoration is generally about two years. Simultaneously, the monitoring time of frost-resistant ecological substrate used in this paper is clearly stipulated in the standard (NB/T 35082-2016) within half a year, and the effect of ecological restoration can be basically not monitored after one year, so the data within two years is reliable and sufficient. The plants selected in this paper are fully grown in half year and one year. Therefore, two years is enough to properly reflect the effect of ecological restoration when this kind of ecological substrate is used on the slope.

3 Methodology

3.1 Selection of slope eco-restoration indicators

Indicators, the typical vehicle for ecological restoration evaluation, must be justified to express as a function of the context of goals and targets (Prach et al. 2019), such as success or failure. For clarity, the definition of the indicators to measure restoration success from Heink and Kowarik (2010) is used in the paper as “An indicator in ecology and environmental planning is a component or a measure of environmentally relevant phenomena used to depict or evaluate environmental conditions or changes or to

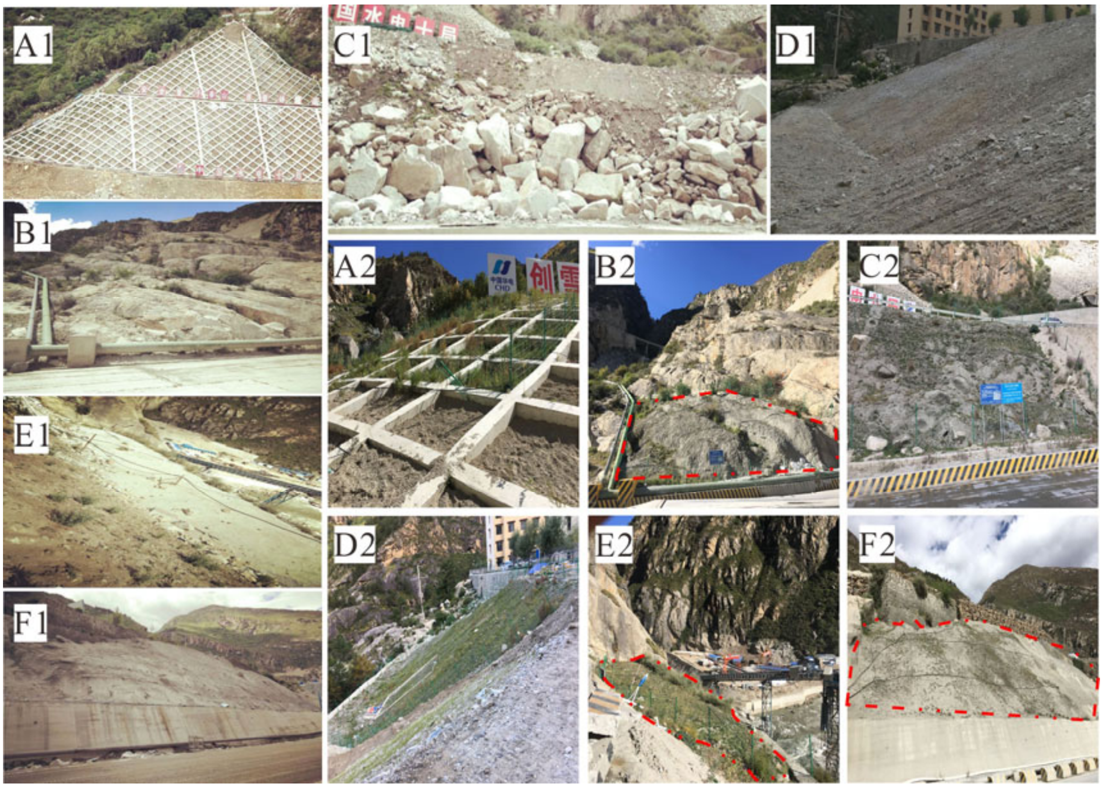

Fig. 2 Pre- and post-implementation restoration for six slopes in the Dagu hydropower project area. A1-A2- soil slope; B1-B2- rock slope; C1-C2- soil-rock slope; D1-D2- spoil slope; E1-E2- construction site slope; F1-F2- hardened slope.

set environmental goals". Particular restoration projects should be informed by specific indicators, hence, Dale and Beyeler (2001) summarized the criteria for appropriate indicators as "Good ecological indicators should meet the following criteria: be easily measured, be sensitive to stresses on the system, respond to stress in a predictable manner, be anticipatory, predict changes that can be averted by management actions, be integrative, have a known response to natural and anthropogenic disturbances and changes over time, and have low variability in response".

At present, the existing research methods cannot effectively evaluate the artificial vegetation restoration in high latitude and high elevation areas. Therefore, a potentially useful evaluation method based on objective indicators for the special restoration evaluation should be exploited, which also could facilitate the transfer of valuable information to other projects. Some scholars have proposed three indictors of soil fertility (Rivera et al. 2014), microbial activity, and vegetation cover can quantitatively characterize the effect of vegetation restoration, but Huang et al. (2018) suggested that the regional characteristics have significantly impact on the assessment outcome if the indictors with improper choice.

In accordance with the requirements of the above mentioned criterions and regional characteristics of southeast Qinghai-Tibet Plateau, four groups of appropriate indicators, topography, erosion, soil quality (refer to substrate), and vegetation, are selected (Table 1). Low precipitation and extreme temperatures have the detriment for the restoration (Maccherini et al. 2018), and they are more sensitive and vulnerable in mountain areas than that in lowlands (Immerzeel et al. 2010). In addition, Xu et al. (2018) pinpointed that the temperature and precipitation changes are dependent on altitude in the mountain region, China. Therefore, the elevation is preferred to represent the variability of temperature and precipitation in our study area. The other indicators of topography, like gradient and aspect, could survey directly at the field, and the shady slopes are convenience to vegetation growth which is different from the lowlands. For erosion (area affected by erosion) and vegetation (vegetation cover, area occupied by exotic/invasive species) indicators, the

Table 1 Pre-selection of slope eco-restoration quality indicators.

Topography	Erosion	Soil quality	Vegetation
Elevation (m) Gradient (°) Aspect	Area affected by erosion (% related to the total area) Estimated erosion rates (Mg/ha·year) Subsurface flows (qualitative)	soil pH Nitrate nitrogen (g/kg) Available phosphorous (g/kg) Available potassium (g/kg)	Vegetation cover (%) Area occupied by exotic/invasive species (% of the total area) Species diversity Above-ground biomass (g/m²) Blow-ground biomass (g/m²)

area influenced by instability and vegetation processes could be measured by photointerpretation. Because there is no long-term runoff monitoring data, it is impossible to quantitatively measure the index data related to subsurface flow. Therefore, the indicators related to the subsurface flows are evaluated qualitatively in this paper, and the protocol gives guidance in order to reduce the subjectivity of the observations, allowing the evaluator to classify landscape integration according to the similarity of the restored area to the surrounding natural landscape. Hence, soil sampling is relatively quantified, and a detailed illustration will be given in the next chapter.

3.2 Slope eco-restoration quality index

Evaluating restoration is not straightforward, but an objective approach can enable the non-scientific public to evaluate restored areas as well. For the framework of ecological restoration assessment, a total of 301 articles spanning 71 journals were identified by Wortley et al. (2013) via the Web of Knowledge database, the results mentioned that the number of empirical evaluations has grown substantially in recent years. Carabassa et al. (2019) selected 55 open-pit mines for the empirical evaluations of ecological restoration, and showed that the weight method is suitable for empirical evaluations of ecological restoration. Roces-diaz et al. (2018) and Carabassa et al. (2019) have obtained a global restoration quality index (RQI) that summarizes the main factors affecting the ecological restoration, using the proximity to target methodology. A weight for each indicator is proposed, according to the reference and expertise of the panel members (Deltoro et al. 2012). Therefore, according to the previous successful research methods, a simplified slope eco-restoration quality index (SERQI) for quantitatively assessing the effects of hydropower project disturbed slope eco-restoration is proposed in this paper. The SERQI is calculated as the sum of all the slope indicators (SI) multiplied by its respective weighting (W):

$$\mathrm{SERQI} = \sum_{x=1}^{n}(\mathrm{SI}_x \times W_x) \quad (1)$$

where, SI ranges from 0 to 1, and W ranges from 0 to 100; n denotes the total number of indicators; x stands for individual indicators.

In order to compare and integrate the evaluation data through a set of individual indicators, a functional curve for each parameter proposed by Carabassa et al. (2019) is introduced to make each indicator standardized, dimensionless, and fully comparable, where 1 represents the maximum quality for restoration and 0 the worst case. However, the functional curve only includes erosion, soil quality, and vegetation, resulting in the critical indicator of topography is missing to standardize. Therefore, the indexes of erosion, soil quality and vegetation are directly obtained from the monitoring and investigation report. According to the field survey, the growth of vegetation on shady slopes (north-facing slopes) is significantly better than on sunny slopes (south-facing slopes) because of the temperature and humidity changed stronger on sunny slopes in Qinghai-Tibet Plateau (Xue et al. 2018). Here, we define that the SI_A equals to 1 in shady slopes, to 0 in sunny slopes, and to 0.5 in other aspect. Usually, the steeper the slope, the more unfavorable for plant growth, and the gradient of 90° is the least suitable for herbaceous plant growth. Hence, the standardized score of gradient indicators can be written as

$$\mathrm{SI}_G = 1 - G/90 \quad (2)$$

where, SI_G is the standardized score of gradient indicator; G is the gradient of the slope, °.

For the elevation indicator, the standardized score can be written as

$$\mathrm{SI}_E = 1 - \sum_{y=1}^{m} \frac{|E_y - E_y^{opt}|}{E_y + E_y^{opt}} / m \quad (3)$$

where, SI_E is the standardized score of elevation indicator; m represents the number of pioneer species; E is the elevation of the slope, m; E_{opt} is the optimum growth elevation and soil depth of vegetation, m.

According to the relevant information and available literatures, the optimum growth elevation for *Poa annua* L., *Festuca rubra* L., *Elymus dahuricus* Turcz. and *Medicago sativa* L. is 3000 m, 4000 m, 3200 m 2300 m, respectively. Meanwhile, the soil depth requirement of the four plants should be 30 cm, 25 cm, 22 cm and 2 m, respectively (Zhang 2007).

3.3 Weight selection of eco-restoration indicators

The method of expert panel weighting (Orsi et al. 2011) is used to rank the indicator per group through a Delphi process (Table 2). The experts involved in the Delphi process were identified from three aspects: personal knowledge, projec t database and literature review. We contacted via email more than 120 people affiliated with universities, governmental agencies, private consultants and corporations around the world. Among the fifteen indicators, topography was the most relevant in the alpine region for the slopes compromise the success of the restoration. As we mentioned before, the precipitation and temperatures are more sensitive and vulnerable in mountain areas than that in lowlands, and can be represented by the proxy variable of elevation (Xu et al. 2018), hence, the indicator weight of elevation reached 20%. The presence of soil quality directly related to the artificial eco-restoration vegetation survival problems in alpine region. In the other words, the success of slope eco-restoration depends on the quality of the habitat construction. Vegetation was rated as the third due to its implications in landscape integration. Furthermore, the evaluation parameters with a weight higher than 5% were considered as a key indicator, which should take into special consideration when assessing the slope eco-restoration success, according to the expert panel and the field observations.

3.4 Collection and monitoring of the substrate

The DG hydropower station in the southeast Qinghai-Tibet Plateau was selected as a case that takes into account the regional characteristics. Six types of slope in the engineering disturbance area were chosen, and corresponding slope ecological restoration measures are used to test these slopes. The information of soil quality and vegetation in post-restoration slope was obtained by medium-term monitoring and laboratory test. These data were statistically analyzing to get key indictors to build the evaluation framework.

Table 2 Weight of the selected indicators according to their importance for slope eco-restoration success measurement after pairwise comparison by experts scoring.

Group	Indicator	Indicator weight (%)	Group weight (%)
Topography	Elevation	20.0	38.4
	Gradient	6.8	
	Aspect	11.6	
Erosion	Area affected by erosion	4.6	10.6
	Estimated erosion rates	3.0	
	Subsurface flows	3.0	
Soil quality	Soil pH	5.0	23.0
	Nitrate N	6.0	
	Available P	6.0	
	Available K	6.0	
Vegetation	Above-ground biomass	4.6	28.0
	Blow-ground biomass	4.6	
	Vegetation cover	11.8	
	Area occupied by exotic/invasive species	3.4	
	Species diversity	3.6	

The soil in the slope eco-restoration in DG hydropower projects is an artificial soil, hence, we should ensure that the slope stability is not damaged when sampling. Five-point sampling method was used to collect the samples in the zone of 1 m×1 m square, and the collection thickness is concentrated around 5 cm~10 cm (Fig. 3). The samples should be evenly mixed into a sealed bag to prevent evaporation, and the weight of each sample is controlled at about 1 kg. Then, the samples would go through the process of air dying, impurity removing (including gravel, grass roots, leaves, etc.), and 0.25 mm sieving. According to the current national standard "Soil Test Method Standard" (GBT 50123-2019), conducting the laboratory test to determine the pH, nitrate nitrogen, available phosphorous, and available potassium. The pH value is mixed into a suspension with a soil-water ratio of 1:2.5 and then measured by electrical measurement; nitrate nitrogen was measured by continuous flow analysis spectrophotometry; available phosphorus was determined by sodium hydroxide alkali dissolution-molybdenum blue colorimetric method; available potassium was using ammonium acetate extraction-atomic absorption method (Huang et al. 2020).

From the end of July to mid-August 2018, six

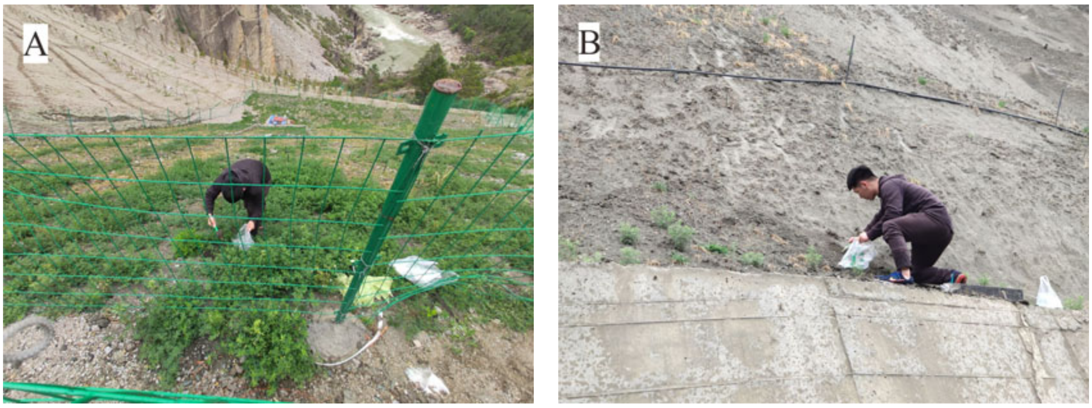

Fig. 3 Working photos of field sampling in the Dagu hydropower project area. A- spoil slope; B- hardened slope.

types of slope eco-restoration in the DG hydropower project area were completed. The effect of slope eco-restoration monitored and sample collected were conducted every 2 to 3 months. Among them, the monitoring sample is consistent with the sample collection sample, and each monitoring indicator includes biomass (above-ground and blow-ground) and vegetation (species diversity). For above-ground, the plant height was measured by ruler. The quantity and diversity of plants were measured by artificial counting and observation. All plants were harvested and taken back to the laboratory. The above-ground biomass was measured by electronic scale after washing by water and then drying in the 60°C oven for one day. For blow-ground biomass, the soil samples were washed with water until roots were only left after samples of each monitoring square are collected. The blow-ground biomass was obtained by weighing the dried roots. Moreover, the Shannon-Wiener index was adopted to calculate the species diversity (Teng et al. 2020), and the formula was as follow:

$$H = -\sum_{i=1}^{s} P_i \ln P_i \tag{4}$$

where H is the species diversity index; s is the number of vegetation species; i represents individuals of different species; P_i is the ratio of the number of i^{th} species to the total number of species, $P_i=N_i/N$; N_i is the number of species i, and N is the total number of species.

4 Results

4.1 Variation characteristics of slope eco-restoration indicators

Soil quality refers to the capacity of a soil to serve a specific land use or function within the boundaries of the ecosystem. Indicators such as pH, nitrate nitrogen, available phosphorous, available potassium, vegetation cover, and species diversity help measure the health or condition of the soil-its quality-in any given place. For six slope eco-restoration projects, the nitrogen varies greatly, while other elements change unapparent (Fig. 4). Due to the addition of cement, the pH value of rock slope, construction hardening surface and soil-rock slope is higher at the initial stage of restoration, and then gradually decreases to be equivalent to the pH value in other slope eco-restoration projects (Fig. 4A). Meanwhile, the substrate is controlled by artificial preparation so that the pH value was controlled within a suitable range for vegetation growth. From Fig. 4B, C, and D, it shows that nitrogen, phosphorus, and potassium presented to reduce first and increase, then decrease with the seasons change trend. The above phenomenon can be explained as follows: 1) the artificial substrate is added with a large amount of nutrients in the initial stage of slope eco-restoration; 2) the soil and water loss in the alpine region is quite serious. In terms of soil quality, the soil slope, soil-rock slope, spoil slope, and construction site slope are superior to the rock and hardened slopes. Unlike the rock and hardened slopes, the substrate is directly cemented on backfilled soil, which provides a continuous fertility cycle for the substrate in the other four type slopes, while the rock and hardened slopes can barely contribute nutrients to the substrate.

During the different demonstration test zones, the vegetation cover and species diversity of soil slope, hardened slope, spoil slope, and construction site slope are relatively superior. The maximum coverage of the above four slopes reached 78%, 71%, 99%, and

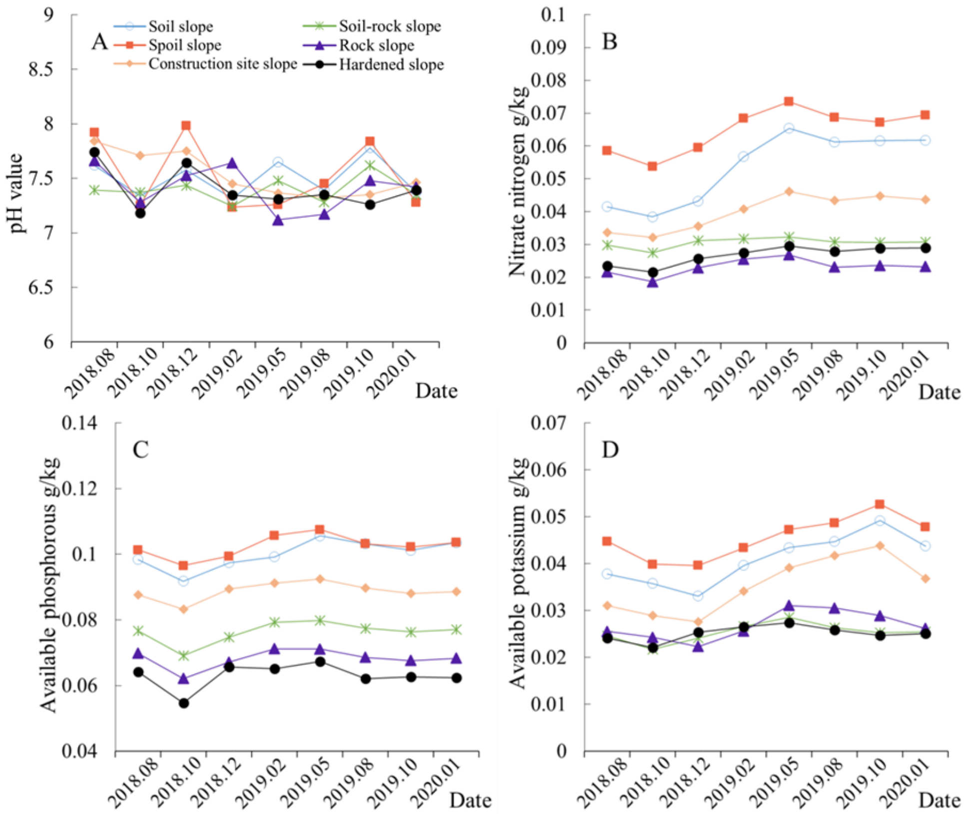

Fig. 4 Monitoring data of different slope eco-restoration soil qualities in Dagu hydropower project area.

99%, respectively, and the species diversity is 1.805, 1.975, 2.205, and 2.275 as well. The vegetation resumes growth early in the following year and grows naturally throughout the year. Thus, it can be seen that the slope eco-restoration has a favorable effect that can adapt to the local ecological environment as soon (Table 3). The eco-restoration performance of rock slope and soil-rock slope, however, are not satisfactory. The maximum coverage of them only reached 63% and 61%, but the species diversity is up to 2.191 and 1.975 (Table 3). For the rock and soil-rock slopes, the large temperature difference in alpine regions and that the rock could not provide a continuous fertility cycle for the substrate makes them difficult to realize the desired goals.

4.2 SERQI calculation and assessment

Using the results of the indicators weight and quality per slope type, the whole SERQI could be calculated. In the literature of Carabassa et al. (2019), the restoration quality index (RQI) is larger than 70, or RQI > 85 with all key indicators more than zero, it could be considered as a good result. Simultaneously, Carabassa et al. (2019) used this criterion to evaluate the open-pit mines rather than the restoration in the alpine region. We propose the consideration of the topography indicator in order to identify the success of engineering disturbed slope eco-restoration in alpine region. Considering that it is more difficult to repair the slope in the alpine region, we lower the standard value slightly. Meanwhile, according to the actual effect of slope restoration in the alpine region, the ecological restoration effect is poor when the $SERQI_x$ (*x* stands for individual indicators) < 60, so we set the $SERQI_x$ as 60 in this paper. Therefore, we define that the slope eco-restoration in alpine region is success when the SERQI > 60. Based on the proposed framework, the results of SIx (x stands for individual indicator) and SERQIx can be seen in the Table 4. Although eight monitoring have been conducted within two years, the latest data of each indicator was used in the process of calculating SERQI, that is, the data in January, 2020, was applied. From the value of SERQI, the ranking of slope eco-restoration effects is: spoil slope (83.28)>soil slope (72.61)>construction sit slope (71.07)>soil-rock slope (65.06)>rock slope (53.66)>hardened slope (43.29).

Table 3 Vegetation cover and species diversity in different slope eco-restoration projects (mean ± standard deviation)

Data Indicators	Slope type	2018.08	2018.10	2018.12	2019.02	2019.05	2019.08	2019.10	2020.01
Vegetation cover (%)	Soil slope	61±1.430	52±1.360	60±1.380	70±1.610	78±1.670	65±1.410	64±1.710	67±1.630
	Rock slope	53±1.250	48±1.410	55±1.420	58±1.490	63±1.540	56±1.340	54±1.450	57±1.580
	Soil-rock slope	55±1.330	52±1.450	56±1.340	59±1.530	61±1.480	59±1.520	53±1.480	56±1.420
	Spoil slope	94±1.910	90±1.880	95±1.940	97±2.130	99±1.890	98±1.860	95±2.070	97±1.930
	Construction site slope	96±1.820	90±1.920	95±1.870	96±1.970	98±2.040	99±1.950	96±1.930	97±2.110
	Hardened slope	65±1.740	61±1.640	64±1.610	68±1.740	71±1.660	68±1.640	66±1.620	67±1.720
Species diversity	Soil slope	1.755±0.041	1.675±0.045	1.695±0.049	1.765±0.048	1.805±0.074	1.739±0.054	1.728±0.049	1.778±0.062
	Rock slope	1.826±0.053	1.759±0.052	1.929±0.064	2.056±0.075	2.191±0.094	1.897±0.065	1.835±0.061	1.881±0.074
	Soil-rock slope	1.956±0.061	1.938±0.073	1.948±0.067	1.973±0.069	1.975±0.087	1.953±0.078	1.957±0.071	1.966±0.092
	Spoil slope	2.113±0.072	2.056±0.081	2.089±0.083	2.183±0.094	2.205±0.104	2.161±0.104	2.137±0.093	2.152±0.117
	Construction site slope	2.157±0.075	2.087±0.076	2.115±0.091	2.214±0.096	2.275±0.113	2.204±0.107	2.185±0.081	2.192±0.121
	Hardened slope	1.757±0.043	1.749±0.061	1.779±0.064	1.786±0.067	1.795±0.065	1.775±0.054	1.765±0.049	1.769±0.064

Table 4 Evaluation results of slope eco-restoration quality index (SERQI) for each slope eco-restoration in Dagu hydropower project area, Tibet.

Group	Indicator	Soil slope		Rock slope		Soil-rock slope		Spoil slope		Construction site slope		Hardened slope	
		SI_x	$SERQI_x$	SI_x	$SERQI_x$	SI_x	$SERQI_x$	SI_x	$SERQI_x$	SI_x	$SERQI_x$	SI_x	$SERQI_x$
Topography	Elevation	0.46	9.20	0.53	10.60	0.55	11.00	0.68	13.60	0.71	14.20	0.54	10.80
	Gradient	0.55	3.74	0.67	4.56	0.49	3.33	0.72	4.90	0.89	6.05	0.61	4.15
	Aspect	1.00	11.60	0.50	5.80	0.50	5.80	1.00	5.80	0.50	5.80	0.00	0.00
Erosion	Area affected by erosion	1.00	4.60	0.50	2.30	0.60	2.76	1.00	4.60	0.80	3.68	0.40	1.84
	Estimated erosion rates	1.00	3.00	0.60	1.80	0.70	2.10	1.00	3.00	0.80	2.40	0.20	0.60
	Subsurface flows	0.90	2.70	0.50	1.50	1.00	3.00	1.00	3.00	1.00	3.00	0.30	0.90
Soil quality	Soil pH	0.00	0.00	0.30	1.50	0.50	2.50	0.90	4.50	0.60	3.00	0.20	1.00
	Nitrate nitrogen	1.00	6.00	0.50	3.00	0.70	4.20	1.00	6.00	0.60	3.60	0.50	3.00
	Available phosphorous	0.90	5.40	0.60	3.60	0.80	4.80	1.00	6.00	0.50	3.00	0.40	2.40
	Available potassium	1.00	6.00	0.60	3.60	0.90	5.40	1.00	6.00	0.50	3.00	0.60	3.60
Vegetation	Above-ground biomass	0.90	4.14	0.40	1.84	0.90	4.14	0.90	4.14	0.60	2.76	0.20	0.92
	Blow-ground biomass	0.60	2.76	0.20	0.92	0.70	3.22	0.80	3.68	0.50	2.30	0.20	0.92
	Vegetation cover	0.67	7.91	0.57	6.73	0.56	6.61	0.97	11.45	0.97	11.45	0.67	7.91
	Area occupied by exotic/invasive species	0.78	2.65	0.83	2.82	0.87	2.96	0.91	3.09	0.95	3.23	0.70	2.38
	Species diversity	0.81	2.92	0.86	3.10	0.90	3.24	0.98	3.53	1.00	3.60	0.80	2.88
SERQI		72.61		53.66		65.06		83.28		71.07		43.29	

5 Discussions and Conclusions

The methodology is designed and tested to help the evaluation of slope eco-restoration in alpine regions, using objective information obtained through field survey, monitoring, and simplified approaches available for a non-specialized public. Compared with other methods for evaluating the success of restoration, such as empirical-statistical model, long-term monitoring, conceptual framework, and attributes analysis (Wortley et al. 2013; Nilsson et al. 2016; Beier et al. 2017), the framework in this paper can quantitatively describe the success of slope eco-restoration. The SERQI value is based on the previous successful ecological restoration evaluation method (RQI value), which is targeted at the region around the middle altitude (Carabass et al. 2019), and the RQI does not consider the characteristics of the special region of the Qinghai Tibet Plateau (Yang et al. 2018). The unique climate and high altitude are the main characteristics of alpine region, compared with RQI value, so the SERQI value takes into account the characteristics of the alpine region (such as elevation information). In general, the SERQI takes the topography indictor into consideration, which can provide an alternative way for the non-specialized public to evaluate the slope eco-restoration not only in alpine region, but in the different regions. Moreover, the methodology is based on multi-indictor which few studies focus on in the Qinghai-Tibet Plateau. The method verification of the slope is restored by the technology invented by our team, its application in other kind of restoration technology could present mismatches in some indicators and reference values, but provides a tradeoff between restoration assessment and technology requirement for engineering disturbed slope.

Among the four categories of indicators selected in this paper, we believe that the topography indicators are the most important and account for the highest weight. Because the main research area in this paper is alpine region, the elevation indicator can best reflect this feature, so the weight reaches 20, which is the highest among all the indicators. The slope aspect affects the duration of sunlight on plants, directly affects the growth of vegetation (Liu 2013), and the gradient of slope also affects whether plants can germinate and grow naturally on the slope for a long time (Xu et al. 2017). In terms of vegetation indicators, these are the second important indicators for slope restoration, because the growth of vegetation determines the success or failure of slope restoration. These indicators selected in this paper are commonly used to reflect the growth of plants, and are often measured in slope ecological restoration. For example, the vegetation cover is the main indicator that can directly observe the quality of slope restoration. Based on the current Energy Industry Standard of the People's Republic of China 'Technical Code for Eco-Restoration of Vegetation Concrete on Steep Slope of Hydropower Projects (NB/T 35082-2016)', soil quality is the key evaluation indicator for the substrate in ecological slope protection engineering, and reasonable soil quality is a necessary condition for sustainable and healthy growth of plants. The standard stipulates that the fraction of available nitrogen, phosphorus and potassium should be larger than 0.06 g/kg, 0.02 g/kg and 0.1 g/kg, respectively. Finally, the erosion indicators are actually closely related to the vegetation indicators. If the vegetation restoration is better, the eroded area and erosion rate of the slope will be lower, Because the vegetation leaves can reduce the surface runoff and the vegetation root system can reinforce soil, which will effectively reduce the soil erosion of slope (Zhang et al. 2015).

In this paper, it can also be seen that the ecological restoration effect of the spoil slope is the best among the five types of slopes, followed by the soil slope, and the rock slope and the hardened slope are the worst. The reason for the phenomenon is that the spoil slope is generally formed by the accumulation of small particles mixed with silt, sludge and dewatered sludge at the bottom of the river after being screened. The spoil slope has higher fertility and better particle size distribution, it is more beneficial for vegetation growth and ecological restoration. The soil slope is mainly composed of sandy soil, which has large particle size, loose structure, poor stability, less nutrient content and nutrient fixation capacity, so the restoration effect of the soil slope is worse than that of the spoil slope. The surface of rock slope and hardened slope are mainly rock and cement respectively, which cannot provide water and fertility for vegetation, leading to the ecological restoration effect is the worst. In comparison, the spoil slope has the best restoration environment compared to the other five kinds of slopes, and its restoration effect is the best.

In general, some of the key indictors are difficulty of achieving consensus among members of the expert panel (Orsi et al. 2011). As a result, the sensitivity and uncertainty of indictors could be taken as a weakness of our framework. A complete slope eco-restoration evaluation index selection system, including topography, erosion, soil quality, and vegetation, was established in the paper based on the existing research and engineering experience. The index selection system sufficient considered the various of the factors selecting and weighting in different type slope, such as, the two type slopes with same restoration technology and growth environment requirements, the indictors are very likely with different weights (Table 2). It highlights that the selecting and weighting of indicators is flexible in our methodology, and practitioners can choose and weight the indictors based on the characteristics of the slope types, the technology used, and the project location, etc. Hence, the paper provided an index selection alternative way, like topography, to make the methodology more practicable in the future.

A comparison of the change features in the slope eco-restoration soil qualities (Fig. 4) and SERQI assessment results (Table 4), three main conclusions could be obtained as follows: 1) the slope types have great influence on the restoration projects with the same technology, making the ranking of the soil quality is spoil slope>soil slope>construction site slope>soil-rock slope>rock slope>hardened slope. 2) The frost-resistant ecological substrate performed well in special region of Qinghai-Tibet Plateau with large temperature difference and short growing seasons, and it is very suitable for the spoil slope, followed by soil, soil-rock, and construction site slopes, and finally rock slope and hardened slope. 3) the SERQI value of each slope is in accordance with the field survey and monitoring information, hence, the simplified framework is applicable for quantitatively assessing the success of engineering disturbed slope eco-restoration in the alpine region. Overall, the methodology could support slope eco-restoration practitioners to making a more objective and quantitative evaluation for the post-implementation restoration. At same time, the demonstration test by using our team's product provides an example that can contribute to improve the development of engineering disturbed slope eco-restoration in the Qinghai-Tibet Plateau. However, the longer the monitoring time is, the more convincing the evaluation of slope ecological restoration effect will be, and the longer-term ecological restoration effect can be monitored and evaluated in the future.

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