

# Stability and micro-topography effects of *Sophora moorcroftiana* community for fixation of sandy land under natural restoration, southern Tibetan Plateau

Chengrui Liao<sup>1</sup>, Haidong Li<sup>2</sup>, Guoping Lv<sup>1</sup>, Meirong Tian<sup>2</sup>, Jiarong Tian<sup>1</sup>, Huihui Shi<sup>1</sup>, and Yannan Xu<sup>1</sup>

<sup>1</sup>Nanjing Forestry University

<sup>2</sup>Nanjing Institute of Environmental Sciences

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## Abstract

The Tibetan Plateau, a vulnerable eco-region for global warming, has huge value of science and practice on ecological restoration to mitigate and adapt to climate change. *Sophora moorcroftiana* shrubs, which are widely distributed in the middle reaches of Yarlung Zangbo River basin, have been recovered on desertified land benefiting from natural restoration during the past decades. However, the effects of habitat conditions in different topographies on population structure and distribution of *S. moorcroftiana* have been rarely reported. Here, we achieve the variation of vegetation and micro-topography of *S. moorcroftiana* population by a series of field surveys with Terrestrial Laser Scanning (TLS) during natural restoration in 2017. The results indicate that the positive correlation between height and CPA reached the 99% confidence level ( $p < 0.01$ ). The plant height was significantly correlated with the elevation and slope ( $r = 0.167$  and  $0.145$ , respectively;  $p < 0.01$ ). While the distribution of *S. moorcroftiana* population decreased along increasing elevation, and the trend of distribution was decreasing firstly, increasing secondly and decreasing finally with increasing slope. The habitat conditions on the southwest slope of approximately  $20^{\circ}$ - $25^{\circ}$  with altitudes of 3593-3643 m most favor to the distribution of *S. moorcroftiana* population in this region. These will help to understand the effect of micro-topography on population structure and distribution of *Sophora moorcroftiana* in southern Tibetan Plateau and assess the effectiveness of natural restoration of *Sophora moorcroftiana* in different topographies.

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Chengrui Liao<sup>1, 2, 3</sup>, Haidong Li<sup>2, \*</sup>, Guoping Lv<sup>1, 2, 3</sup>, Meirong Tian<sup>2</sup>, Jiarong Tian<sup>1, 2, 3</sup>, Huihui Shi<sup>1, 3</sup>, Yannan Xu<sup>1, 3, \*</sup>

<sup>1</sup>Nanjing Forestry University, Nanjing 210037, China

<sup>2</sup> Nanjing Institute of Environmental Sciences, Ministry of Ecology and Environment, Nanjing 210042, China

<sup>3</sup> Centre of Co-Innovation for Sustainable Forestry in Southern China, Nanjing Forestry University, Nanjing 210037, China

E-mail address: [nfuxyn@njfu.edu.cn](mailto:nfuxyn@njfu.edu.cn); [lihd2020@163.com](mailto:lihd2020@163.com)

Telephone numbers: 18905188069; 13951793216

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desertified land benefiting from natural restoration during the past decades. However, the effects of habitat conditions in different topographies on population structure and distribution of *S. moorcroftiana* have been rarely reported. Here, we achieve the variation of vegetation and micro-topography of *S. moorcroftiana* population by a series of field surveys with Terrestrial Laser Scanning (TLS) during natural restoration in 2017. The results indicate that the positive correlation between height and CPA reached the 99% confidence level ( $p < 0.01$ ). The plant height was significantly correlated with the elevation and slope ( $r = 0.167$  and  $0.145$ , respectively;  $p < 0.01$ ). While the distribution of *S. moorcroftiana* population decreased along increasing elevation, and the trend of distribution was decreasing firstly, increasing secondly and decreasing finally with increasing slope. The habitat conditions on the southwest slope of approximately  $20^{\circ}$ - $25^{\circ}$  with altitudes of 3593-3643 m most favor to the distribution of *S. moorcroftiana* population in this region. These will help to understand the effect of micro-topography on population structure and distribution of *Sophora moorcroftiana* in southern Tibetan Plateau and assess the effectiveness of natural restoration of *Sophora moorcroftiana* in different topographies.

**Key word:** population structure; spatial distribution; micro-topography; *Sophora moorcroftiana* ; Tibetan Plateau

## 1 Introduction

Ecological restoration is the process of assisting the restoration of a degraded ecosystem and can provide substantial benefits that enhance quality of life (Benayas et al., 2009; Suding et al., 2015; McDonald et al., 2016). It has emerged as a critical tool to reverse and ameliorate the current loss of functions and services in the degraded ecosystems (Mijangos et al., 2015). Natural and artificial restoration are two important strategies of ecological restoration (Jin et al., 2014; Barral et al., 2015).

Since the 1990s, a series of ecological restoration programs have been widely launched to improve these increasingly devastating degraded grassland ecosystems in the arid and semi-arid areas of China, including the establishment of a national ecological security shelter zone and the active restoration of forest and shrubs on the Qinghai-Tibetan Plateau (Li et al., 2015; Yan et al., 2018; Li et al., 2019). Increasingly researching for ecological restoration, the widely held notion that natural regeneration has limited conservation value and that active restoration should be the default ecological restoration strategy has been challenged (Crouzeilles et al., 2017). ChaZdon (2008) has reported that natural restoration can achieve great success in degraded ecosystems. Deng et al. (2016) have shown that natural restoration is the better option for maintaining the stability of water resources in arid and semi-arid regions. Although the natural restoration are increasingly being implemented throughout the world and have produced some benefits to improve the degraded ecosystems (Benayas et al., 2009; Huang et al., 2019), few scientific reports have been published on the effect of natural restoration in Tibetan Plateau (Liao et al., 2020a). In 2015, the General Office of State Council of China has proposed that the natural restoration should be recorded as the main strategy during ecological restoration. In recent decades, natural restoration has been conducted by the removal of degrading factors and mainly involves the secondary succession of shrubs and grassland, following prohibition of overgrazing, extensive reclamation, excessive firewood collection in Tibetan Plateau. The previous study has found that the natural restoration has advantaged to maintain the fine particles in aeolian sandy land, compared with artificial restoration (Liao et al., 2020a). However, less research has focused on the changes of plant growth and population structure in different topographies during the natural restoration, especially for the population of *Sophora moorcroftiana* (Benth.) Baker (Fabaceae).

The Tibetan Plateau, which is generally known as the “Third Pole” of Earth, is one of the most ecologically vulnerable regions in terms of grassland degradation (Liao et al., 2019; Li et al., 2019). In many dune habitats, shrub species are the crucial element in rehabilitating a degraded grassland ecosystem, due to greater substrate stability and decreased sand movement (Liu and Zhang, 2018; Wang et al., 2019). Shrub species are distributed widely across almost the whole Tibetan Plateau and exposed to the exclusive harsh environments, such as low oxygen, drought, salinity and cold in Tibetan Plateau (Zhang et al., 2016; Li et al., 2017).

While, *Sophora moorcroftiana* (Benth.) Baker (Fabaceae), one of drought-resistant endemic and dominant shrub species in Tibet, has advantage to deal with these multiple stresses. *S. moorcroftiana* is a perennial leguminous shrub with blue-purple flowers and mainly dominates in the valleys of the middle reaches of the Yarlung Zangbo River (Cheng et al., 2017). It is a unique *Sophora* characterized by strong drought, solar radiation and sand burial resistance, and regarded as an ideal species for studying acclimatization to climatic factors (Zhao et al., 2007; Guo et al., 2014). This species enables the fixation of sand dunes, avoiding the formation of shifting sands and subsequent desertification, and thus it plays an important role in ecological restoration (Liu et al., 2006; Zang and Sun, 2019). Although *S. moorcroftiana* has had much attention from researchers, for example the adaptability of *S. moorcroftiana* to elevation as well as to sand burial (Zhao et al., 2007) and the predictor of biomass for *S. moorcroftiana* in Tibet (Zhang et al., 2016), little information is available on the mechanisms of micro-topography on natural restoration of *S. moorcroftiana* population.

For shrubs, topography (micro-topography) is an applicable predictor of aspect and slope that often correlate with distribution of soil nutrients and spatial pattern of species (Azizi and Montazeri, 2018). The micro-topographic relief is often regarded as one of the main drivers of fine-scale environmental heterogeneity (Oddi et al., 2019). Despite the importance of micro-topography on the species distribution and the growth of dominant shrubs, the research of its quantification is still rudimentary on the remote area like the Tibetan Plateau due to cost and technical challenges (Li et al., 2019). A more recent active remote sensing technology, terrestrial Light Detection and Ranging (LiDAR) imaging systems now provide unprecedented ability to characterize micro-topographic structure and vegetation parameter at very fine scales over large areas (Davis et al., 2019). The airborne (ALS) and terrestrial laser scanning (TLS) are two types of laser scanning systems. While TLS (spatial accuracy within millimeter) is ground-based LiDAR that produces orders of magnitude higher point cloud density than ALS (spatial accuracy of 5-10 cm) over smaller areas for capturing shrub structure and micro-topography (Stovall et al., 2019). TLS have been proven as a new powerful tool for extracting vegetation structure and micro-topography in various fields, such as forest ecology (Davis et al., 2019), wetland ecology (Stovall et al., 2019), hydrology (Cassidy et al., 2019), and geomorphology (Calsamiglia et al., 2018). However, few studies have been conducted to extract the structure of population and micro-topographic factors and assess the spatial distribution of *S. moorcroftiana* during natural restoration, based on TLS in southern Tibetan plateau.

Here we conducted a series of field surveys with terrestrial laser scanning (TLS) to achieve the variation of micro-topography and spatial pattern of *S. moorcroftiana* population, and then analyzed the effect of micro-topography on *S. moorcroftiana* population during natural restoration in southern Tibetan Plateau. This study specifically aims to address two research questions: (1) How did the individual growths change in the different topographies of sampling plot of *S. moorcroftiana* population. (2) What are the impacts of micro-topographic factors on population structure and spatial pattern of *S. moorcroftiana* for natural restoration in southern Tibetan Plateau.

## 2 Methods

### 2.1 Study sites

The site of this study was located in the middle reaches of Yarlung Zangbo River basin in Naidong district of Shannan City, Tibet of China (91.585 °E, 29.258 °N, 3560 m average above sea level). This region belongs to the semi-arid plateau temperate monsoon climate area. The temperature is low with unclear seasons. The annual daily mean temperature is approximately 8.2 (from -18.3 in January to 30.1 in July). During the last decade, this region has the annual precipitation of approximately 382.3 mm, mostly ranged from June to September. The soil is mainly aeolian sandy soils with low contents of soil organic matter and total nitrogen, which is highly susceptible to erosion (Liao et al., 2020a).

## 2.2 Experiment design and data collection

The experiment was initiated in 2017 at the natural shrubland of *S. moorcroftiana* population within a little other plant species, such as *Oxytropis sericopetala*, *Stipa bungeana* Trin., *Orinus thoroldii*, et al., which had undergone over decade of natural restoration. The degradation had happened in this region before 2000 due to the overgrazing and firewood cutting (Shen et al., 2012), however there was visible improvement for vegetation coverage to 2017 during decade of natural restoration (Fig. 1). Three topographies (micro-topographies) measuring 10 ha (100 x 100 m) each were selected separately along the streamway in the same alluvial fan. The margin of alluvial fan was a fixed sand land with flat area (T1) (Fig. 1b and Table 1). The middle of alluvial fan was a semi-fixed sand land at the west slope of approximately 25deg (T2) (Fig. 1c and Table 1). The top of alluvial fan was also a semi-fixed sand land at the northwest slope of approximately 35deg (T3) (Fig. 1d and Table 1). Three of 5 x 5 m small quadrats were set along a diagonal line within each topography for field survey and sampling. For each quadrat, the location, species, vegetation coverage, height, wide (WC) and narrow (NC) crown diameters, elevation and slope were recorded. The crown projection area (CPA) was simply calculated as the area of an ellipse (Zhang et al., 2016). The soil samples were collected and detected as the background characteristics at the beginning of the experiment (Table 2).

In each topography, 3D point cloud data was acquired by a RIEGL VZ-400i TLS on June 30, 2017. The VZ-400i TLS has an  $\pm 5$  mm accuracy at a range up to 800 m and capture the point cloud unit at a speed up to 500,000 points per second, with a field view of 360deg horizontal (H) x 100deg vertical (V) (<http://www.riegl.com/>). Depending on complexity of topography, we used different configurations for plot-level scans to maximum acquisition of the ground surface and vegetation paramant (Fig. 2). The TLS was placed at the center of T1 and eight surrounding locations approximating the cardinal directions, with the distances (approximately 30 m) from the center point, due to the uniform distribution could comprehensively capture point clouds in the flat and open terrain (Fig. 2a). While for the T2 and T3, four of six scans were conducted on the ridge to take advantages of locations (Fig. 2b).

## 2.3 LiDAR data processing

### 2.3.1 Plot cutting and pre-processing

For all scans in each topography, each point cloud was first merged by RiScan Pro software to form a comprehensive point cloud of plot based on the location and reference targets of each scan, such as the house and surveyor's poles of plot (Li et al., 2019). And then, one big plot of 50 x 50 m was cut from each point cloud of plot, using LiDAR360 software. We removed the noise and discriminated ground vs. non-ground points through this procedure. The digital elevation model (DEM) and digital surface model (DSM) were generated by the triangulated irregular network (TIN) interpolation with a spatial resolution of 0.05 m.

### 2.3.2 Vegetation and micro-topography metrics

Based on the DEM and DSM, the canopy height model (CHM) was derived with a 0.05 m resolution (Li et al., 2019; Liao et al., 2020b). The location, height and CPA of individual shrub within the CHM were detected, computed and exported by "rLiDAR" package from R (R x64 3.6.1.lnk) statistical software (R Core Team, 2014). The slope and aspect was derived from the 0.05 m DEM using the 'terrain' tool in LiDAR360 software. The micro-topography parameters (including elevation, slope and aspect), matched with the location of individual shrub, were extracted by R.

## 2.4 Data analysis

### 2.4.1 Population structure

The plant height, regarded as one of the morphological characteristics, was directly and accurately extracted from LiDAR data (Luo et al., 2015). Therefore, height classes were used to explain the structures of *S. moorcroftiana* population, which was an undershrub species and does not have notable annual rings. All *S. moorcroftiana* individuals, captured by single tree segmentation of LiDAR, were classified into different classes based on the vegetation height (Class 1 was less than 30 cm; 30 cm were added gradually from Class 2 to 4 groups; Class 5 was more than 120 cm) which were consulted from previous researches (Yang et al., 2011). The relationship between CPA and height was fitted by a linear model in each topography. A normal distribution curve was used to analyze the plant height distribution structure in each topography.

### 2.4.2 Spatial pattern analysis

The relationship between spatial distribution of *S. moorcroftiana* population and spatial covariate (elevation, slope and aspect) was estimated by nonparametric estimation of the dependence of a spatial point process on spatial covariates in this study. The LiDAR data was captured as finite set spatial points, with the locations of individuals ( $y$ ). Additionally, the values  $Z(u)$  of a spatial covariate (elevation, slope and aspect) at every spatial location  $y$  were extracted from micro-topography metrics. The  $y$  as a realization of a spatial distribution of individuals  $Y$  with density function  $\lambda(u)$  depending on  $Z(u)$  was modeled as follow,

$$\lambda(u) = \rho(Z(u)) \quad (1)$$

where  $\rho$  is a resource selection function reflecting preference for particular micro-topographic conditions in ecological applications where the points are the locations of individual organisms (Baddeley et al., 2012).

## 3 Results

### 3.1 Changes in population structure of *S. moorcroftiana* under different topographies

The population coverage, plant height and CPA in different topography had obvious difference (Table 3). The mean coverage of these *S. moorcroftiana* populations was 58%, 34% and 30% in T1, T2 and T3, respectively. For different topography, T2 had the maximum mean height of 0.74 m and largest mean CPA of 4.13 m<sup>2</sup>, respectively. The plant heights followed the order of T2 (0.74 m) > T3 (0.54 m) > T1 (0.43 m), while there was no significant difference between T1 and T3 for CPA value. The total number of individuals was decreasing trend along T1 (2750), T2 (1475) and T3 (554). However, the height distribution structure in different topography was consistent (Fig. 3). The distribution of height classes followed the normal distribution curve ( $p < 0.001$ ) and the class 2 of (0.3-0.6) m was most prominent in all survey plots. The percent of class 2 reached to 83.2%, 80.5% and 89.2% in T1, T2 and T3, respectively. The class 1 reached to 13.9 % in T1 and the class 3 reached to 13.7 % in T2. The significant linear positive correlation ( $p < 0.01$ ) was shown between height and CPA of each *S. moorcroftiana* populations in Fig. 4. The regression slope of linear equation followed the order of T3 (0.33) > T1 (0.20) > T2 (0.09).

### 3.2 Spatial distribution of *S. moorcroftiana* population

#### 3.2.1 Elevation

Fig. 5 and Fig. 6 showed the changes of individual distribution of *S. moorcroftiana* extracted in each topography along elevation. In three topographies, the elevation spans from 3550 m (T1) to 3695 m (T3). The population density decreased with increasing elevation (Fig. 5). The  $\rho$  value spanned from 1.7 to 0.1 and showed the decreasing trend along elevations, with the largest and smallest values in T1 and T3, respectively

(Fig. 6). However, there were some differences for the different topographies. The decreasing trend along elevations was showed in T1 and T3, with the  $\rho$  value of 1.7-0.5 and 0.4-0.1, respectively. While the  $\rho$  value for T2 had increased minimally from 0.2 to 0.5 with increasing elevation. In general, the height of individual *S. moorcroftiana* shrubs was positively related to elevation from 3550 m to 3695 m ( $r = 0.167$ ;  $p < 0.01$ ) (Fig. 7).

### 3.2.2 Slope

The spatial distribution of *S. moorcroftiana* population for different topography along slope was showed in Fig. 8 and Fig. 9. The order of overall slope in different topographies was T3 (35°) > T2 (25°) > T1 (5°). The value of slope ranged between 0° and 80° in T1 and spanned from 0° to 84° in T2 and T3. Although the spatial distribution of *S. moorcroftiana* population in different topography along slope had differences, there was similar to the overall trend, which was decreasing firstly, increasing secondly and decreasing finally with increasing slope (Fig. 9). In T1, the  $\rho$  value was decreasing from 1.74 to 0.85 with the slope of 0° - 2.6°, and then increasing to 1.52 with the slope of 2.6° - 15.8°, and finally showed irregular fluctuation with the maximum value of 2.84 at 48° and minimum value of 0.01 at 42°. However, there was obvious regulation for the changes of  $\rho$  value along slope in T2 and T3. In T2, the decreasing trend was happened before the slope of 10.6° and after the slope of 20.3°, with the  $\rho$  value of 1.88 - 0.42 and 0.75 - 0.03, respectively. While the maximum  $\rho$  value was 0.27 at 50.6° and the minimum  $\rho$  value was 0.10 at 5.6° in T3. In general, the individual height of *S. moorcroftiana* population exhibited significant correlation with slope from 0° to 84° ( $r = 0.145$ ;  $p < 0.01$ ) (Fig. 7).

### 3.2.3 Aspect

Fig. 10 and Fig. 11 showed the spatial distribution of *S. moorcroftiana* population had large difference for the changes of aspect in different topographies. The minimum  $\rho$  value was showed on the north for all of topographies. In T1, the  $\rho$  value in different aspects follows the order of Southwest (1.23) > Southeast (1.21) > South (1.10) = West (1.10) > East (1.06) > North (0.62). In T2, the  $\rho$  value was Southwest (0.78) > Northeast (0.68) > East (0.63) > West (0.55) > South (0.53) > North (0.38). While the maximum  $\rho$  value was 0.26 on the Northeast and then followed as East (0.23), South (0.21), West (0.16), North (0.13) decreasingly in T3.

## 4 Discussion

The growth and distribution of species and habitat condition, including soil, climate and topography et al., are inseparable (Piao et al., 2012; Liu et al., 2014; Liao et al., 2020). In this study, there are no significant differences for the soil properties between different topographies (Table 2). However, there are significant differences for the individual growth between different topographies. The experimental plots were all located on the same alluvial fan with the same climate overall. While local modification of the climate by topography and vegetation produces microclimates at the land-air interface (Zellweger et al., 2019). Therefore, the micro-topographic condition was main constraints that affected the changes of microclimates. And hence the spatial complexity may be important for adaptations to climate change (Kooijman et al., 2019). The warming temperature and the change in precipitation have provided the positive effects of vegetation dynamics in recent decades in this region (Li et al., 2015; 2016). Thus, the unreasonable human activity, such as overgrazing, extensive reclamation and excessive collecting live plants for firewood, remain the dominant factor caused aeolian sandy land development severely in 1990s in this region (Shen et al., 2012; Li et al., 2016). Ecological restoration programs, including active restoration (i.e. planting the artificial forest and shrubs, conversion of cropland to grassland, shrub or forest, and establishing the sand-protecting barriers) and natural restoration (i.e. forbidding grazing or collecting firewood and controlling the number of livestock), have been launched and conducted successfully since 2000. In this study, the coverage for *S. moorcroftiana* population shows well after decades of natural restoration (Fig. 1). Population structure is

the synthetic action of biological characteristics, environmental factors, and intraspecific interactions which can be used to reflect the succession dynamics and development trends of a population (Liu and Zhang, 2018). The relationship between CPA and height was fitted well by a linear model in each topography from the field survey ( $p < 0.01$ ) in this study. Therefore, the plant height of *S. moorcroftiana* population was regarded as the measure of age grade. This study showed that the height structure of *S. moorcroftiana* population approximated a Gaussian distribution model (Fig. 3). The population structure was dominant for the seedlings in 2011, however the number of individuals was dominant for the adults of 30-60 cm in 2017. Compared with the early study in 2011, the age structure of *S. moorcroftiana* population increased significantly to 2017. Aggregated spatial distribution patterns are commonly observed in many restored ecosystem and small individuals showed higher degree of aggregation than large individuals (Zhao et al., 2012). The present study also found that the height class of less than 90 cm (class 1, 2, 3) had higher degree of aggregation than those of more than 90 cm (class 4, 5) for each topography (Fig. 3), and this phenomenon of aggregation was observed more clearly with increasing elevation and slope.

It is commonly agreed upon in the academic community that climate change can cause alterations to the structure of communities and also cause changes in the spatial distribution of terrestrial populations (Gelviz-Gelvez et al., 2015). Therefore, the micro-topography was also an important driver of individual distribution. Revealing the spatial distribution of *S. moorcroftiana* population contribute to illustrate the effects of various micro-topography on the dispersal and growth of *S. moorcroftiana*. Our results showed that the correlations between the individual height of *S. moorcroftiana* population and micro-topography (elevation and slope) reached the 99% confidence level ( $p < 0.01$ ), however there were obviously differences for the individual distribution on different topographies. Although the distribution of *S. moorcroftiana* population decreased along increasing elevation, there was a peak value at 3624 m (T2) (Fig. 6). There was similar to the overall trend of spatial distribution for *S. moorcroftiana* population along increasing slope, with some different changes minimally happened after approximately 20°. While the *S. moorcroftiana* population was mainly distributed on the southwest in T1 and T2 and on the northeast in T3. Diamond et al. (2019) reported that the spatial distribution of relative water levels is changed by the wetland micro-topography and affected individual distribution and growth. However, for sandy ecosystem, the changes of solar radiation with micro-topography also must be taken into account (Li et al., 2019). In general, the west would receive excessive solar radiation and evaporation in the afternoon, and this is not conducive to survival of plants. Therefore, there was little distribution of individuals on the west in all of micro-topography in this study. Generally speaking, the short time of solar radiation and fine condition of water have been found at the shade slope, north slope of mountain, and it was beneficial for vegetation growth. Therefore, the moving sandy land was mainly distributed on the north of Yarlung Zangbo River, while the fixed sandy land was mostly located in the south of Yarlung Zangbo River, which was the north slope of mountain. However, there were minimum density of vegetation at the north slope from the micro-topography. One conjecture, the effect of low temperature in alpine valley, was submitted for the difference between overall and micro-topography scale. Less solar radiation with lower temperature at the shade slope blocked the survival of plants. Comprehensively analyzing the structure, distribution and growth of population, we concluded that the habitat conditions on the southwest slope of approximately 20°-25° with altitudes of 3593-3643 m most favor to the natural restoration of *S. moorcroftiana* population on aeolian sandy land.

## 5 Conclusion

The TLS, a new and powerful tool, was used to accurately extract the parameters of vegetation and micro-topography during the natural restoration of *S. moorcroftiana* population on the degraded land in this study. The changes of structure of *S. moorcroftiana* population and effect of micro-topography on spatial distribution of *S. moorcroftiana* population after natural restoration on an extremely degraded land were evaluated by the field investigation and TLS scans in the middle reaches of Yarlung Zangbo River in 2017. Since 2008, the effectiveness of natural restoration for *S. moorcroftiana* population had gradually improved in the Yarlung Zangbo River valley, Shannan city and the vegetation coverage had reached 30% - 58% in

2017. The dominant age structure of *S. moorcroftiana* population were adults. The heights of individual shrubs ranged from 0.43 m to 0.74 m in different topographies, and the CPA ranged from 0.52 m<sup>2</sup> to 4.13 m<sup>2</sup>. The west slope of approximately 25° with altitudes of 3593-3643 m (T2) has highest individual growth. The positive correlation between height and CPA reached the 99% confidence level ( $p < 0.01$ ).

The measured elevation and slope spanned from 3550 m to 3695 m and from 0° to 84°, respectively. The elevation and slope exhibited significant positive correlations with plant height ( $r = 0.167$  and  $0.145$ , respectively;  $p < 0.01$ ). However, the distribution of *S. moorcroftiana* population decreased along increasing elevation, while the overall trend of distribution of *S. moorcroftiana* population was decreasing firstly, increasing secondly and decreasing finally with increasing slope. There was little distribution of individuals on the west and north. Therefore, our results showed that the habitat conditions on the southwest slope of approximately 20°-25° with altitudes of 3593-3643 m most favor to the distribution and growth of *S. moorcroftiana* population in this region. In order to be able to advise managers on the effectiveness of natural restoration in producing ecological benefits of high value for community distribution and growth, along with optimized strategies of ecological restoration in the restored process, it is necessary to monitor and evaluate the structural development of population and spatial distribution of individuals after natural restoration.

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## Author contributions

Haidong Li conceived and designed the research, Yannan Xu helped to improve the hypothesis, Chengrui Liao wrote the paper, Haidong Li, Chengrui Liao and Guoping Lv carried out the field work and the analysis, Meirong Tian, Jiarong Tian, Huihui Shi and Yannan Xu contributed to the discussion, and paper revision. (All photos were photographed by Haidong Li in this article).

## Competing interests

The authors declare no competing interests.

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Table 1 The detail information of selected topographies

Topography	Elevation/m	Slope/°	Aspect
T1	3550-3557	5	-
T2	3593-3643	25	West
T3	3685-3695	35	Northwest

Table 2 Soil properties of different topographies for *S. moorcroftiana* population in depth of 0-10 and 10-20 cm

Topography	Depth/cm	pH	SBD/g·cm <sup>3</sup>	SMC/%	SOM/g·kg <sup>-1</sup>	TN/g·kg <sup>-1</sup>	TP/g·kg <sup>-1</sup>
T1	0-10	8.11	1.70 ± 0.11 a	10.18 ± 0.35 a	18.52 ± 3.60 a	1.54 ± 0.24 ac	0.48 ± 0.05 ab
	10-20	8.06	1.60 ± 0.14 a	7.92 ± 1.75 a	17.42 ± 1.05 a	1.63 ± 0.49 ac	0.59 ± 0.13 b
T2	0-10	8.11	1.61 ± 0.02 a	9.07 ± 1.42 a	11.73 ± 6.24 a	1.21 ± 0.16 ab	0.42 ± 0.01 a
	10-20	8.43	1.68 ± 0.05 a	9.15 ± 0.76 a	7.92 ± 6.54 a	1.91 ± 0.32 c	0.45 ± 0.04 a
T3	0-10	8.56	1.69 ± 0.03 a	9.43 ± 0.92 a	15.70 ± 0.82 a	1.68 ± 0.37 ac	0.38 ± 0.02 a
	10-20	8.36	1.66 ± 0.03 a	8.24 ± 1.31 a	14.77 ± 2.36 a	1.49 ± 0.21 b	0.40 ± 0.06 a

Values are mean  $\pm$  SD. Numbers followed by different lower-case letters within the same column have significant differences ( $p < 0.05$ ). SBD refers to soil bulk density; SMC refers to soil moisture content; SOM refers to soil organic matter; TN refers to total nitrogen; TP refers to total phosphorus.

Table 3 Height classes and basic parameters of *S. moorcroftiana* population in different topographies.

Topography	Population coverage/%	Individuals of different classes	Individuals of different classes	Individuals of different classes
		Class 1(%)	Class 2(%)	Class 3(%)
T1	58	382(13.9)	2287(83.2)	65(2.4)
T2	34	68(4.6)	1187(80.5)	202(13.7)
T3	30	34(6.1)	494(89.2)	22(4.0)

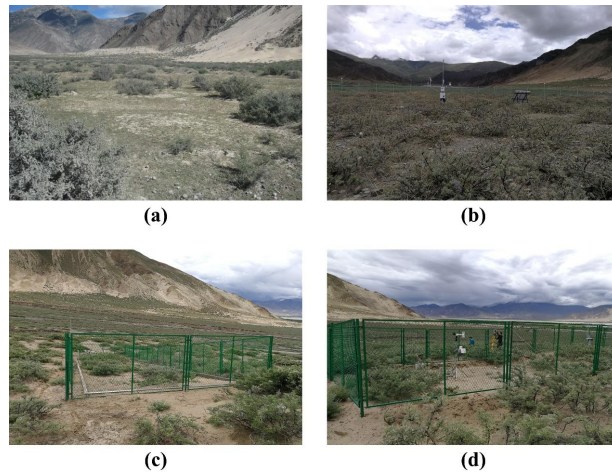


Fig. 1 The natural restoration of *S. moorcroftiana* population in the middle reaches of Yarlung Zangbo River basin from 2010 to 2017. (a) was taken in September 17, 2010 in Gongga County, Tibet. (b), (c) and (d) Photos that were taken from T1, T2 and T3 in July 2<sup>nd</sup>, 2017, respectively, in Naidong district of Shannan City, Tibet.

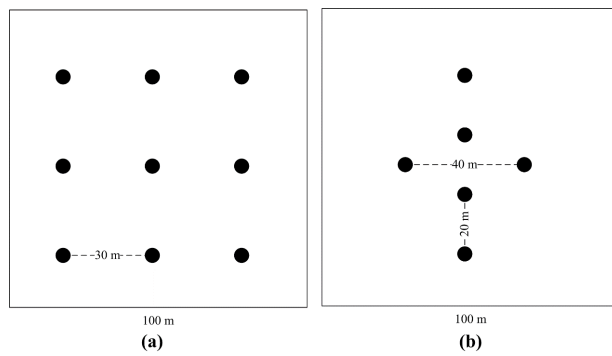


Fig. 2 Spatial arrangement of TLS (closed dot) in different experimental plot.