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Original Article

Identification and spatial pattern analysis of alpine timberline by remote sensing methods in Yarlung Zangpo Grand Canyon

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Abstract: As an important ecotone, the alpine timberline is the boundary between closed-canopy montane forest and alpine vegetation, and is highly sensitive to global and regional climate changes. We provided a way to identify and extract the alpine timberline in Yarlung Zangpo Grand Canyon Nature Reserve by using remote sensing data and spatial analysis based on land use/land cover classification and NDVI distribution characteristics. Combining DEM data, the influence of slope and aspect on the distribution of alpine timberline was explored. The results showed that the alpine timberline in Yarlung Zangpo Grand Canyon is transitional timberline, with the upper boundary approximately distributed at the elevation of 3422-4373 m, the lower boundary at approximately 3270-4164 m, with a width of about 110-280 m. Alpine timberline was mainly distributed on steep and very steep slopes ranging from 25° to 45°. The maximum elevation of both the upper and lower boundaries occurred on steep slopes. The distribution of alpine timberline varies with aspects, with sunny slopes having a higher boundary than shady slopes.

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1 Introduction

Alpine timberline is the transitional zone between closed-canopy montane forest and treeline. As an important ecotone, it is highly sensitive to global and regional climate changes (Körner 1998, Holtmeier 1994). Many factors such as climate, topography, and disturbance (moisture availability, volcanic eruption, glacier fluctuation, snow avalanche, human activities, etc.) at different scales define the alpine timberline, although the dynamic change of alpine timberline is regarded as an indicator of climate change (Holtmeier 2003, Heikkinen et al. 2002, Case et al. 2014, Elliott et al. 2020). At global scale, temperature is considered the limiting factor controlling the distribution of alpine timberline as low temperature restricts biochemical processes of tree growth (Paulsen 2004, Smith 1994, Richardson et al. 2009, Holtmeier 2005). Studies have shown that the elevation of global alpine timberline is closely related to the average temperature of the growing season (Körner 2004, Paulsen et al. 2014). However, at local and regional scales, strong environmental heterogeneity interferes with the relationship between timberline elevation and temperature (Pecher et al. 2011). Topography has an important influence on the structure and function of mountain areas, changing environmental factors such as light, heat, water, soil depth, and soil surface fertility, resulting in changes in mountain ecological phenomena and processes (Fang et al. 2004). Topographic factors (aspect, slope, etc.) affect surface solar radiation, atmospheric and soil temperature, snow-free period length, etc. The influence of topography on the location and distribution of alpine timberline has been observed in many mountains in the world (Dai et al. 2012, Kullman 2001, Greenwood et al. 2015, Macias et al. 2013). Shen et al. (2014) found that the sunny slope of the high mountain was dry at night in the early growing season, prone to radiation cooling, and with more freezing injury days than that of the shady slope, which had a significant impact on tree regeneration near the timberline. Wang et al. (2012) described the dynamics response of *Betula ermanii* population and climate change on different slopes aspect in the Changbai Mountains, and found that *Betula ermanii* population on eastern slopes had the most positive response to temperature. Some authors found no significant difference in the average height of alpine treeline in northwest Yunnan, but it was evident that the monsoon climate conditions cause more clouds on the south-facing windward slope, and the average height of alpine treeline was slightly lower than other slope aspects (< 30 m) (Wang et al. 2013). Current timberline research mainly focuses on revealing the relationship between timberline distribution and climate factors, and seldom considers the influence of terrain factors to define the timberline distribution (Dearborn et al. 2017). It is of great significance to scientifically evaluate the response and feedback of mountain forests to climate change by accurately revealing the structure and pattern of changes in alpine timberline, and finding out the correlation between the distribution of alpine timberline and geographical factors in the study area.

In the traditional method, topographic maps were combined with field survey to observe the morphological characteristics and distribution of trees, so as to determine the elevation of alpine timberline (Beaman et al. 1962). However, due to the limitation of terrain and climate, it is difficult to identify timberline in a plateau canyon area. With the development of space remote sensing (RS) technology, using image classification to obtain the boundary of closed-canopy forest patches or the distribution of sparse forest close to timberline has become an important method for extracting the alpine timberline (Solaimani et al. 2011, Diaz-Varela et al. 2010, Kamil 2009). However, the alpine timberline obtained by RS image classification is only the boundary between different types of ground objects patches, and it is generally difficult to reflect the transitional characteristics of vegetation near the timberline. In addition, researchers have proposed different standards for identifying and defining the timberline, which often result in different accuracies of the extracted timberline or difficulty in mutual comparison and verification (Liu et al. 2016). The vegetation index can quantitatively record and reflect vegetation information, and can show the spatio-temporal variation of vegetation at the pixel scale (Hwang et al. 2011). Normalized difference vegetation index (NDVI) has a good correlation with canopy cover and leaf area index, and is widely applied to the detection of vegetation change, vegetation greenness and vegetation status (Myneni et al. 1991), which can help to distinguish the vegetation density (Singh et al. 2012) and its dynamics (Dunn et al. 2011). Using NDVI to quantitatively identify the transitional changes of vegetation near the timberline can improve the accuracy of RS image classification for extracting alpine timberlines (Liu et al. 2016).

The Yarlung Zangpo Grand Canyon is located downstream of the Yarlung Zangpo River, in the eastern Himalayan area. It is an area where the strongest climate and tectonic action in the world can be found, with elevations ranging from 155 m to over 6000 m. This area has the most complete vertical vegetation zonation in the world (Deng et al. 2011), consisting of low mountain tropical monsoon rainforest, mountain subtropical evergreen and semi-evergreen broad-leaved forest, middle-mountain warm temperate evergreen coniferous forest, subalpine cold temperate evergreen coniferous forest, alpine subarctic shrub and meadow, alpine subarctic periglacial, and significantly high mountain frigid zone ice and snow. It has the natural timberlines with the highest elevation worldwide, and is a suitable area to study the distribution pattern of alpine timberline (Wang et al. 2017, Shi et al. 2015). Previous studies have found that in the southern wing of the eastern Himalayas, the mountain dark coniferous forest, mainly distributed between 3100 and 3900 m, are composed of *Abies delavayi var. motuoensis* and *Abies delavayi*, while the alpine scrub and alpine meadow mainly distributed between 3900 and 4200 m, are composed of *Rhodendron spp.* and *Betula utilis*. In the middle and low elevation sites of the Yarlung Zangpo River, the mountain dark coniferous forest was mainly distributed between 3200 and 4000 m, represented by *Abies spectabilis* and *Picea likiangensis*, while the alpine scrub and alpine meadow mainly distributed between 4000 and 4400 m (Zheng 1987). However, there are relatively few studies on the alpine timberline in this area. The existing studies mainly focus on the vegetation ecology and its relationship with climate change, while the characteristics of transitional changes and spatial distribution of alpine timberline in vertical space have not been studied in a comprehensive manner (Xu et al. 2009, Fan et al. 2008). In this paper, RS data and Geographic Information Systems (GIS) technology were used to extract the alpine timberline, and a preliminary study was conducted on the alpine timberline in the Yarlung Zangpo Grand Canyon from the NDVI characteristics and geographic spatial patterns (elevation, slope, aspect) of vegetation, to find out the correlation between timberline distribution and geographic factors in the study area. This can lay a foundation for further research on the dynamics of alpine timberlines and provide a scientific basis for regional ecological conservation under climate change.

2 Materials and Methods

2.1 Study area

The Yarlung Zangpo Grand Canyon starts from Daduka Village, Pai Town, Milin County (with an elevation of about 3000 m) in the north, to Baxika Village, Medog County (with an elevation of about 115 m) in the south, and the horizontal spatial range is 29°05′-30°20′N , 94°39′-96°06′E, with a total area of 9168 km² (Fig. 1). Owing to the uplift of the Tibet Plateau, the southwest monsoon in South Asia has been intensified, and the arc-shaped mountains protruding south of the Himalaya Mountains forced the southwest monsoon to move northward around the east side of the plateau, making the Yarlung Zangpo Grand Canyon a natural water vapor and heat

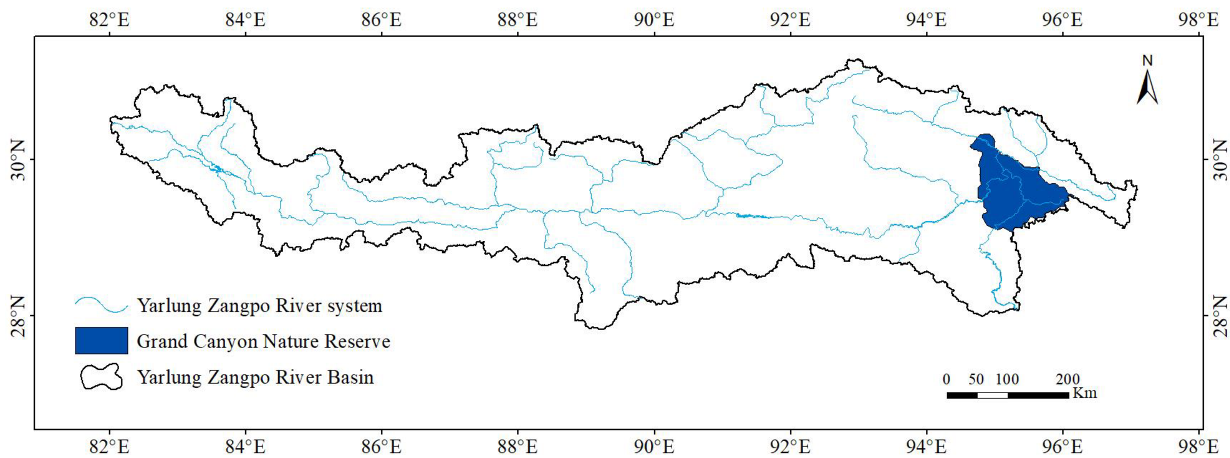

Fig. 1 Location of the Yarlung Zangpo Grand Canyon Nature Reserve.

transport channel, with transport capacity of the water vapor up to 500-1000 g·cm^{-1}·s^{-1} (Liu et al. 2007). The complex climatic conditions, ecological environment and special topography contribute to special types of vegetation in the Grand Canyon. In this mountainous area, with the tropical rain forest as the basis, the above vertical belt is composed of wet vegetation types. In the monsoon area with distinct dry and wet seasons, the air humidity in the short dry season is still relatively high. Forests are dominated by hemlock and fir forests which demand humidity (Yang et al. 1996). The distribution characteristics of vertical vegetation belt are obviously different from those in other mountainous areas. The timberline here arises in unique conditions and is worth investigating.

2.2 Land use and land cover classification

Landsat 8-OLI RS images at Level 1T processing level, without clouds, in the early vegetation season were selected from USGS Earth Explorer (https://earthexplorer.usgs.gov/). The images were from June 2, 2019 and June 11, 2019, and the scene numbers were p134/r039, p134/r40, p135/r039, p135/r40, with a spatial resolution of 30 m. Object-oriented RS image analysis technology was used. Based on the secondary classification system for land use in the second national land survey (Xu et al. 2019), the land use and land cover in the study area was divided into 15 types, including paddy field, dry land, forestland, shrub land, open forestland, other woodland, high coverage grassland, medium coverage grassland, low coverage grassland, ditch, lake, glaciers and permanent snow, mud flat, bare land, and bare rock gravel land. The classification results are shown in Fig. 2. The study area is dominated by forestland and grassland, with forestland area accounting for 56% and grassland area occupying 27%. The accuracy was evaluated by ENVI 5.1 software. The accuracy and Kappa coefficient obtained were 87.9% and 0.76, respectively.

2.3 Slope and aspect

The Digital Elevation Model (DEM) of the study area was re-projected, clipped in ArcMap 10.4, and the slope and aspect were calculated. DEM raster data was derived from ASTER GDEM (v2) (http://gdem.ersdac.jspacesystems.or.jp/), with a spatial resolution of 30 m and a vertical accuracy of 17 m. The 6S (Second Simulation of the Satellite Signal in the Solar Spectrum) model was used to complete the atmospheric radiation correction to obtain the surface reflectance data, and the DEM data was used to conduct the radiative topographic correction to compensate the surface reflectance difference caused by the topographic relief. According to the operation

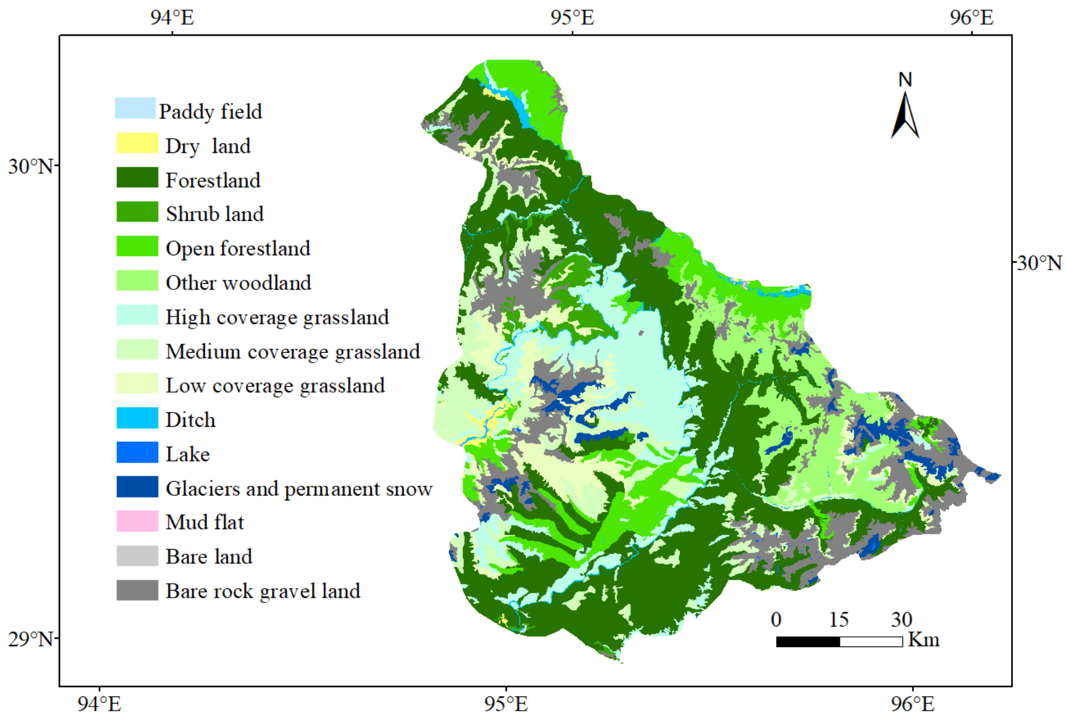

Fig. 2 Classification of land use and land cover in the Yarlung Zangpo Grand Canyon Nature Reserve.

rules of forest resources planning and design investigation in Tibet, the slope was divided into 6 grades in this study (Fig. 3): flat slope (0°-5°), gentle slope (5°-15°), slightly steep slope (15°-25°), steep slope (25°-35°), very steep slope (35°-45°) and critical slope (> 45°). The aspect was divided into 8 grades in this study (Fig. 4): due north (337.5°-360°, 0°-22.5°), northeast (22.5°-67.5°), due east (67.5°-112.5°), southeast (112.5°-157.5°), due south (157.5°-202.5°), southwest (202.5°-247.5°), due west (247.5°-292.5°), northwest (292.5°-337.5°).

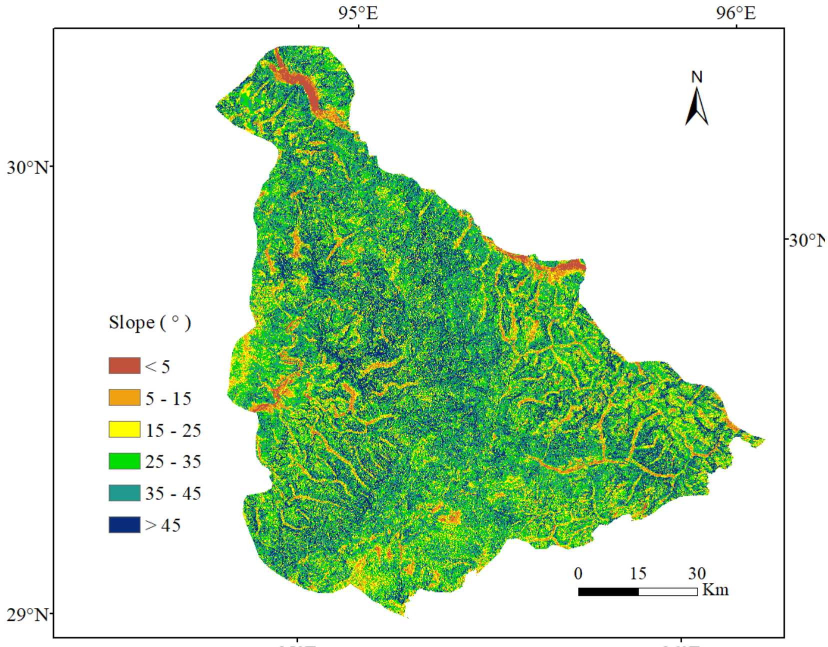

Fig. 3 Slope map of the Yarlung Zangpo Grand Canyon Nature Reserve.

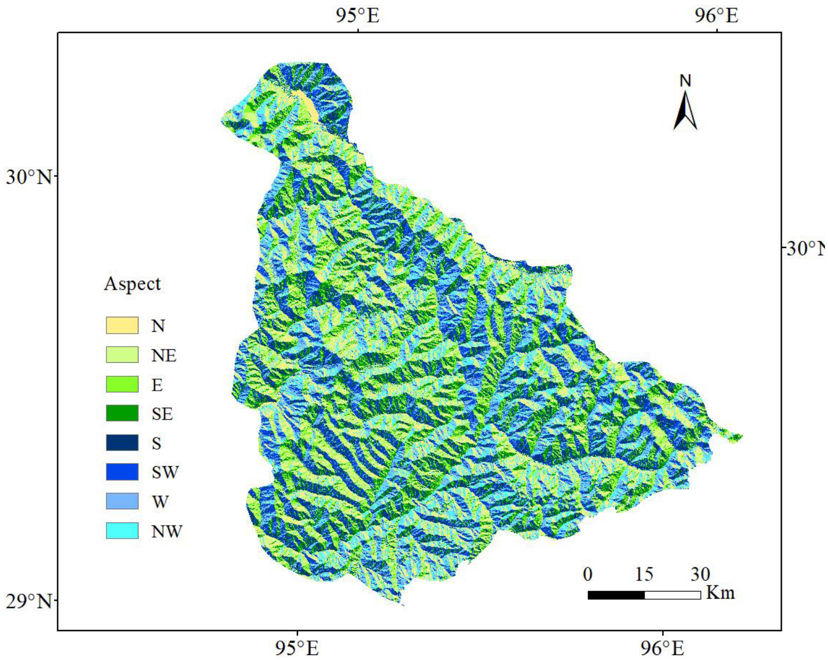

Fig. 4 Aspect map of the Yarlung Zangpo Grand Canyon Nature Reserve.

2.4 Extraction of ridge lines

Ridge lines were obtained based on the analysis of terrain surface water flow (O'Callaghan et al. 1984). In terms of hydrophysical processes, ridges and valleys represent water dividing and water catchment, respectively. The ridge lines generally coincide with the regional watershed and can be obtained by the watershed extraction and transformation by using ArcMap 4.0 (Liu et al. 2018). The specific process was to perform neighborhood analysis on the DEM data to solve the mean value, which was subtracted from the original DEM data, and the result is reclassified to extract the positive landform (i.e., the topography of neotectonic uplift area or the topography relatively higher than the adjacent area); hydrological analysis is conducted to fill sinks in the original DEM data, and the flow direction and the runoff accumulation are calculated, respectively. The runoff accumulation data was smoothed, reclassified and multiplied with the positive landform to obtain the ridge lines (Fig. 5).

2.5 Extraction of alpine timberline

In this study, the alpine timberline refers to the alpine timberline ecotone in a broad sense, that is, the distribution area of sparse forestland between mountain coniferous forest (i.e., forestland in land

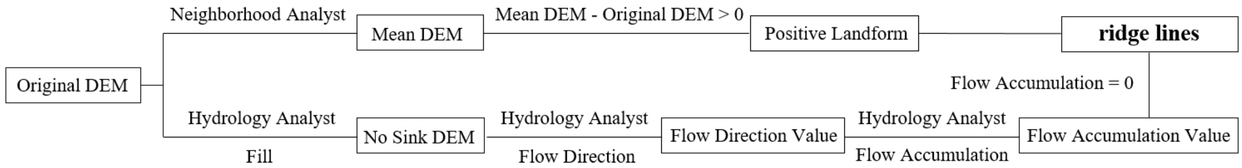

Fig. 5 Calculation flow chart of ridge lines.

use and land cover classification map) and alpine scrub and alpine meadow (i.e., high coverage grassland in land use and land cover classification map). The boundary of the mountain coniferous forest closest to the ridge line is the lower boundary of the alpine timberline, which is the alpine timberline in a narrow sense. The boundary of the alpine scrub and alpine meadow farthest from the ridge line is the upper borderline of the alpine timberline. NDVI can well monitor the growth status of vegetation, vegetation coverage and net productivity, with a numerical range of -1~1. A negative value indicates that the ground cover is cloud, water, snow and other features, and 0 indicates rock and bare soil. A positive value shows that there is vegetation coverage. As the elevation increases, different types of vegetation correspond to different NDVI values. Therefore, the NDVI and land use and land cover classification map in the early stage of vegetation season based on the elevation information can quantitatively distinguish the range of the alpine timberline. The NDVI can be calculated from RS images, where $\mathrm{NDVI} = (\rho_{NIR} - \rho_{RED})/(\rho_{NIR} + \rho_{RED})$, ρ_{NIR} is the reflectance in near-infrared wavelength, and ρ_{RED} is the reflectance in red wavelength. For Landsat 8-OLI data, band 5 (B5) is the NIR band, and band 4 (B4) is the RED band.

The 5% and 95% quantiles of the NDVI data of the forestland and the high coverage grassland in the land use and land cover classification map were used as thresholds to determine the vegetation. The extraction results were verified and revised with the high-resolution images provided by the Google Earth platform. In order to avoid the summit syndrome triggered by factors such as wind erosion, debris flow gully, and lack of soil matrix around the summit, the pixels with a vertical distance of less than 50 m from the ridges were eliminated. The NDVI grid collections of the maximum elevation of the forestland and the minimum elevation of high coverage grassland on each slope indicated the lower and upper boundaries of the alpine timberlines, respectively (Fig. 6).

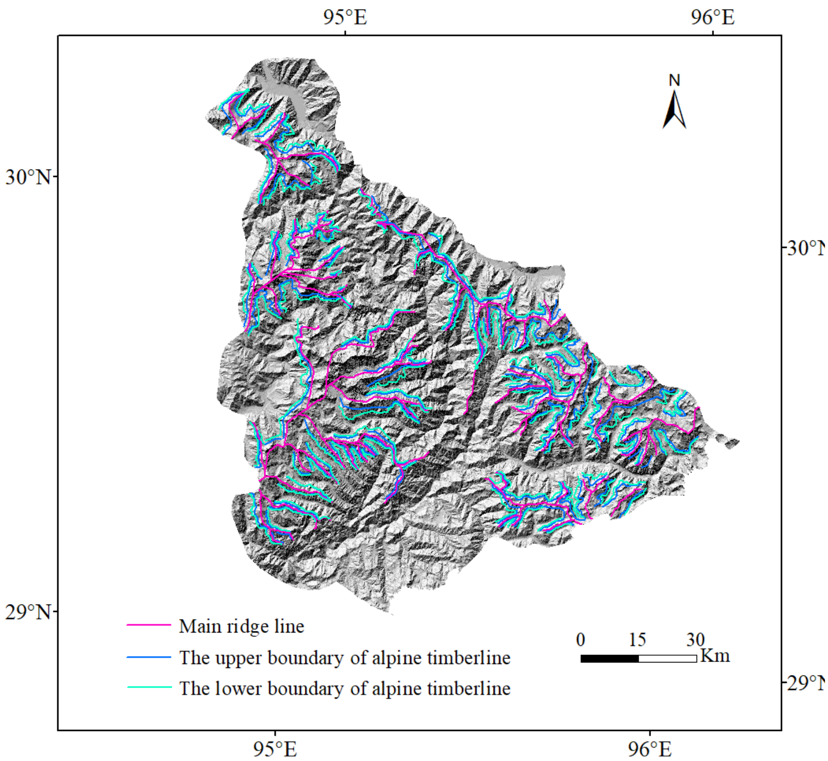

Fig. 6 Extraction results of the upper and lower boundaries of alpine timberline of the Yarlung Zangpo Grand Canyon Nature Reserve.

3 Results and Discussion

3.1 Characteristics of NDVI and elevation near the alpine timberline

At the beginning of the vegetation season, there are significant differences in NDVI between the mountain coniferous forest and the alpine scrub and alpine meadow in the Yarlung Zangpo Grand Canyon

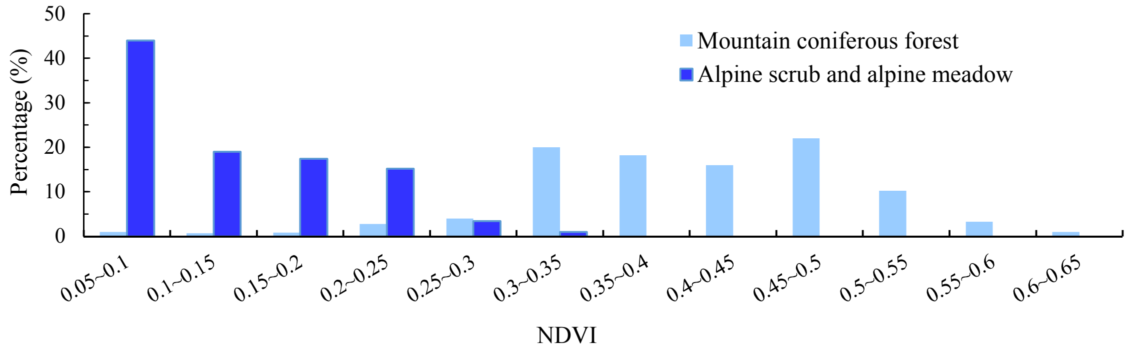

Fig. 7 NDVI frequency distribution of mountain coniferous forest and alpine scrub and alpine meadow.

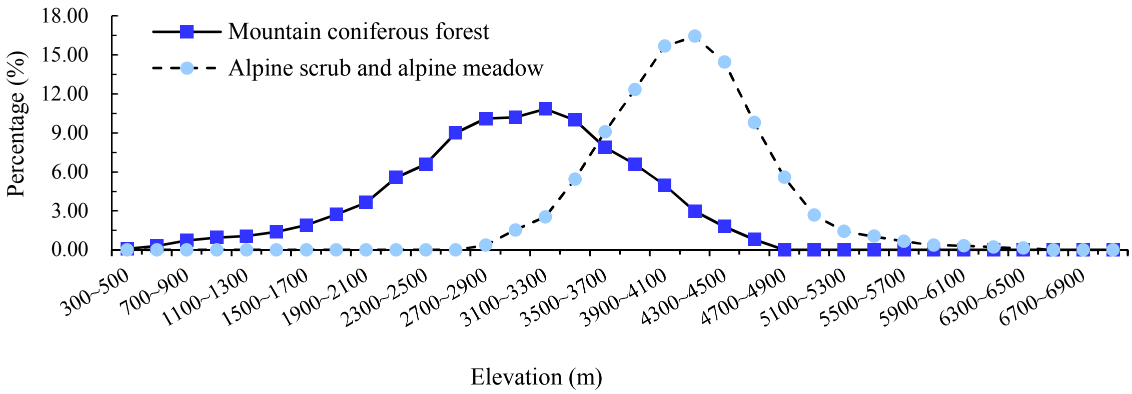

Fig. 8 Elevation distribution of mountain coniferous forest and alpine scrub and alpine meadow.

(Fig. 7). The NDVI of mountain coniferous forest generally varies from 0.30 to 0.55, and the NDVI of alpine scrub and alpine meadow is generally between 0.05 and 0.25. An 86% of mountain coniferous forest was distributed at an elevation of 2400-4000 m, and the most concentrated distribution can be found at an elevation of about 3200 m, reaching 11%, and there is almost no distribution of mountain coniferous forest at above 4900 m. The 96% of alpine scrub and alpine meadow was distributed at an elevation of 3500-4700 m, and the most concentrated distribution was observed at an elevation of 4200 m, reaching 16%. Within the vertical space range of 3200-4200 m, the area of mountain coniferous forest decreases, while the area of alpine scrub and alpine meadow increases, and the mountain coniferous forest transition to the alpine scrub and alpine meadow. Above 4200 m, the area of alpine scrub and alpine meadow gradually reduces and there is almost no distribution of mountain coniferous forest and alpine scrub and alpine meadows above about 4500 m and 5500 m, respectively (Fig. 8).

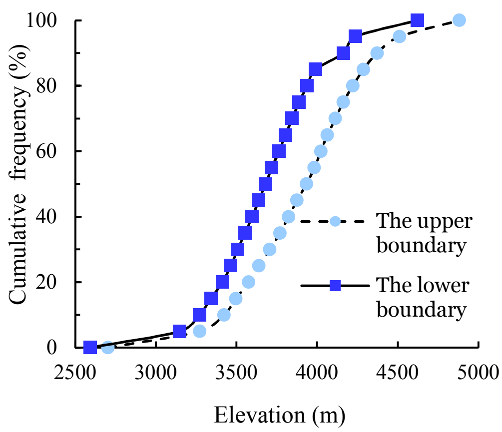

Fig. 9 The cumulative frequency of the elevation of the upper and lower boundaries of alpine timberline.

3.2 Elevation distribution of alpine timberline

Cumulative frequency statistics were made on the elevation of the upper and lower boundaries of alpine timberline in the Yarlung Zangpo Grand Canyon (Fig. 9). It was found that 90% of the upper boundary of timberline is distributed at an elevation of 3422-4373 m, with an average elevation of 3901 m. 90% of the lower boundary is distributed at an elevation of 3270-4164 m, with an average elevation of 3677 m. The transitional alpine timberline has a width of 110-280 m.

3.3 Relationship between the spatial patterns of alpine timberline and slope

Different slopes receive different solar radiation, which causes the changes in the air temperature, ground temperature and other ecological factors, thereby leading to differences in the distribution of timberline. The timberline elevations within each slope range were summarized (Table 1). An Analysis of Variance (ANOVA) test was applied using SPSS software to determine whether the distribution patterns were statistically different from the "baseline" (i.e., the distribution of a topographic variable over the whole study area). Results showed that the slope and aspect of the alpine timberline were significantly different from those of the whole study area ($P<0.05$), and the significance level was 0.008 and 0.029, respectively. 75.5% of the alpine timberline in the study area was distributed on steep and very steep slopes, 11.2% on flat slopes, gentle slopes and critical slopes. The maximum elevation of the upper and lower boundaries of alpine timberline were distributed on steep slopes, and the minimum elevation was found on critical slopes and flat slopes, indicating that significantly low or high slope was not suitable for the existence of alpine timberline. Within a slope of 25°, as the slope increased, the proportion of timberline also gradually increases, with the accumulated proportion of timberline reaching 21%, the average elevation of timberline gradually rising. The average elevations of the upper and lower boundaries of alpine timberline were around 3860 m and 3627 m, respectively, indicating that the elevation of timberline was relatively consistent in this slope range. Within the slope of 25°~45°, as the slope increased, the proportion of timberline gradually increased, with the accumulated proportion of timberline reaching 74%, the average elevation constantly dropping. The average elevation of the upper and lower boundaries of timberline were around 3907 m and 3692 m, respectively, suggesting that this slope range was the major distribution area of timberline, and the larger the slope, the greater the elevation difference in the timberline distribution. For only 5% of timberline, slope exceeded 45°. At lower timberline elevations, the average elevations of the upper and lower boundaries were around 3835 m and 3628 m, respectively. This is because the steep mountain slopes may cause poor soil, matrix instability, landslides, mudslides, and avalanches, which will disturb the distribution pattern of timberline.

It should be mentioned that the difference in slope direction in the Alps is not obvious. The forest vegetation on all slopes can reach the highest elevation of local forest distribution in the whole Alps (Paulsen et al. 2010). The influence of slope on the distribution of mountain forest is different in regions with different climate types. The slope difference of the elevation of timberline in humid climate area was small (<30-50 m), while in arid climate area was moderate (<100 m) (Treml et al. 2008). Different research objectives or data acquisition methods may lead to different research conclusions on the influence of slope aspect on alpine timberline distribution.

3.4 Relationship between the spatial patterns of alpine timberline and aspect

Different aspects affect the solar radiation received by the ground and the angle of intersection between the ground and the prevailing wind direction, resulting in changes of natural factors such as light, heat, water, and soil that restrict the growth of vegetation (Fang et al. 2004), hence causing a difference in the vegetation in different aspects, and different aspect characteristics of the distribution of alpine timberline (Lin et al. 1985). Statistics were calculated for the distribution of timberline in eight aspects (Table 2), and it was found that the distribution of alpine timberline in different aspects in the study area had certain differences (Fig.

Table 1 Distribution of alpine timberline within different slope range

Types of slope	Slope range (°)	Proportion (%)		Average elevation (m)	
		Upper boundaries	Lower boundaries	Upper boundaries	Lower boundaries
Flat slope	0-5	0.68	0.48	3850	3580
Gentle slope	5-15	5.51	5.60	3858	3626
Slightly steep Slope	15-25	15.07	11.47	3871	3674
Steep slope	25-35	28.90	29.77	3925	3715
Very steep slope	35-45	45.02	47.29	3888	3668
Critical slope	>45	4.82	5.39	3835	3628

10). In general, the elevation of the timberline was higher on the south aspect than on the north aspect, and there was no obvious difference between the west aspect and the east aspect. The minimum average elevation of the upper and lower boundaries of alpine timberline were on northeast and north aspects, at 3811 m and 3609 m, respectively; the maximum values all were on southeast aspect, at 3948 m and 3751 m, respectively. For the upper boundaries of alpine timberline, the average elevation was more than 3900 m except due north and northeast aspect, and the difference between due east and due west aspect was only 1 m. For the lower boundaries of alpine timberline, the average elevation was lower than 3900 m except for the southeast aspect, and the difference between due east and due west aspect was 23 m.

The upper and lower boundaries of alpine timberline on sunny slopes were higher than on shady slopes. A possible reason is that as the largest water vapor channel on the Tibet Plateau, the Yarlung Zangpo Grand Canyon is affected by the warm and humid air from the Indian Ocean, thus the Grand Canyon is significantly rainy, and it has a southeast warm and humid climate, so the precipitation difference between the sunny slope and the shady slope is small. While the sunny slope receives more solar radiation and higher temperature, so the timberline migrates to higher elevation. Meanwhile, the temperature differences caused by solar radiation will affect biotic processes in forest soil such as nutrient and carbon mineralization, immobilization, and respiration. These processes, in combination with abiotic phenomena related to the adsorption capacity of the mineral soil, will have direct effects on the provision of environmental services (Armando et al. 2018). Studies have pointed out that in temperate and tropical regions that are not limited by topography, man-made, and other factors, the alpine timberline on the sunny slopes is higher than that on shady slopes. For example, the elevation difference between the timberline on sunny slopes and shady slopes in the temperate humid climate of the Alps reaches 100 m (Holtmeier 2003).

4 Conclusions

As an important landscape boundary of the alpine natural belt, alpine timberline is the product of the long-term comprehensive effect of climate and ecosystems. Remote Sensing data and spatial analysis technology were used to identify and extract the alpine timberline in the Yarlung Zangpo Grand Canyon, and NDVI data from the early vegetation season were used to correct the alpine timberline obtained by the image classification method, so as to realize the spatial expression of the distribution of alpine timberline. Combining ASTER GDEM data, the terrain factors (slope, aspect) were calculated to explore the influence of terrain on the elevation of alpine timberline elevation. The results showed that the alpine timberline in the Yarlung Zangpo Grand Canyon Nature Reserve was a transitional timberline, with the upper boundaries distributed at 3422-4373 m, the lower boundaries at 3270-4164 m, and a width of about 110-280 m. According to the field investigation of the Qinghai-Tibet Plateau Integrated Scientific Investigation Team of Chinese Academy of Sciences in

Table 2 Elevation of alpine timberline in different aspects

Aspect	Proportion (%)		Average elevation (m)	
	Upper*	Lower*	Upper*	Lower*
Due north	11.67	11.13	3822	3609
Northeast	12.59	10.71	3811	3681
Due east	10.89	11.57	3941	3682
Southeast	12.91	12.91	3948	3751
Due south	13.19	13.77	3912	3687
Southwest	14.51	15.01	3919	3689
Due west	11.86	13.02	3942	3659
Northwest	12.38	11.88	3909	3648

Notes: Upper* and Lower* refer to the upper boundary and lower boundaries.

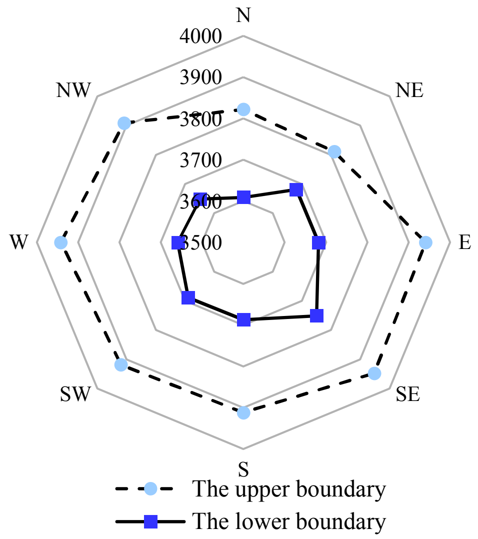

Fig. 10 Elevation (m) of alpine timberline in different aspects.

the area of Namjagbrawa Peak, the elevation of the montain coniferous forest was about 3200-4100 m in the valley on the north side of Namula, 3250-4150 m in the vicinity of Deyangla, and 3400-4200 m in the southwest of Mirin County (Peng 1984). The identification method used in this study found results similar to the field investigation results, which further proves the feasibility and reliability of this method.

This study provided a method for easily identifying the alpine timberline high efficiency, high accuracy and with less restrictions due to terrain costs. The timberline detection metric can also be applied to estimate timberlines in other mountainous regions. The relationship between the distribution of the alpine timberline and geographic factors can be explained to certain extent. This study is expected to lay the foundation for further research on the possible responses of alpine timberline to global and regional climate change, provide help for the protection of regional alpine ecosystem, and offer data support for theoretical research on global alpine timberline. However, affected by the quality and interpretation accuracy of RS images, the extraction results of alpine timberline may have certain deviations, and only the influence of macro-terrain on the distribution of alpine timberline was considered. In alpine valley areas with complex topography, it is necessary to consider the impact of micro-terrain on the distribution of timberline in future studies. Besides, in order to further reveal the causes of the distribution of alpine timberline, it is required to continue to track multi-period RS data, and combine fixed-point and fixed-location research to analyze the photosynthetic characteristics of vegetation, understory soil temperature, temperature and humidity status, soil particle size, microorganisms and enzyme activities, and pay more attention to the long-term observation and simulation research on the dynamics of alpine timberline at the regional scale under climate change. In this way, more scientific bases can be provided for studying the spatial distribution and mechanisms that influence alpine timberline, and for predicting the response of alpine timberline to future climate changes.

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