Research Article

Distribution Characteristics of the Alpine Treeline and Vegetation Response to Climate Change of Taibai Mountain, China

Dan Wang, Shuheng Li, and Shuyao Gao

College of Urban and Environmental Sciences, Northwest University, Xi'an, 710127 Shaanxi Province, China

Correspondence should be addressed to Dan Wang; xzuniversity@yeah.net

Received 1 April 2022; Revised 16 July 2022; Accepted 2 August 2022; Published 13 August 2022

Academic Editor: Qingzhi Wang

Copyright © 2022 Dan Wang et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Climate change significantly affects global forest ecosystems, and the alpine treeline is sensitive to global warming. The alpine treeline data using high-resolution remote sensing images during four periods from 1987 to 2020 at Taibai Mountain are extracted. The dynamic change process of the alpine treeline and the response of vegetation near the alpine treeline to climate change are analyzed. The results showed that the alpine treeline of Taibai Mountain was primarily distributed in the range of 2266-3692 m, and the average elevation of the alpine treeline showed a trend of “rising-decreasing.” The elevation of the alpine treelines of the sunny slopes were much higher than that of the shady slopes, and the highest values typically appeared on slopes and steep slopes of 15-35°. Vegetation is sensitive to temperature changes, and it typically displays a synchronous increase and decrease. However, there was a lag in the precipitation of approximately one year, and the rising temperatures of the sunny slopes were not conducive to vegetation growth. The vegetation will be dominated by a trend of unsustainable improvement in the future, and there exists a risk of continuous vegetation degradation on the northern slopes. However, a warm and humid climate will be conducive to vegetation growth above the alpine treeline.

1. Introduction

The alpine treeline, as the boundary area where mountain vegetation and the habitat conditions undergo significant transitional changes, is an important indicator that reflects climate change [1–4]. The formation and change in the treeline are primarily affected by topographic factors, climatic factors, and human activities [5–7]. Taibai Mountain is the highest peak in the Qinling Mountains in eastern China. Its alpine timberline, an important ecological boundary in the alpine belt, is extremely sensitive to regional climate change [8]. Due to the distribution at high altitudes, the vertical vegetation band spectrum has obvious differentiation, and it is rarely affected by human activities. These conditions can better reflect climate change [9, 10]. Significant changes in the global climate and its effects on vegetation growth have received increasing research attention, and quantitative studies regarding the distribution of alpine treelines at different time scales are helpful.

The alpine treeline is the intersection of forest lines that are composed of the boundary of closed forest land and sparse vegetation zones, such as shrubs and grasslands, above this altitude [11, 12]. Jiang et al. combined a digital elevation model (DEM) and the normalized difference vegetation index (NDVI) to obtain the altitude of the Taibai Mountain treeline area that ranged primarily from 3400 to 3450 m. In addition, the temperature in the treeline area increased as a whole from 1980 to 2013, and this indicated that a continuous increase in temperature would have a negative impact on the cold-tolerant vegetation in the alpine treeline area [13]. Zhai et al. used the Vaganov-Shashkin (VS) model to analyze the physiological process of the radial growth of Larix chinensis and its response to climatic factors, and it was concluded that temperature was the dominant factor limiting the growth of tree species in the treeline [14]. He et al. extracted the vegetation index of Taibai Mountain using remote sensing images from May 1979 to May 2009 and found that the vegetation NDVI had an
obvious vertical difference, and high altitude vegetation was more sensitive to temperature change as compared with low altitude vegetation [15]. Chen established tree-ring chronologies on the southern and northern slopes of the same altitude by using core samples and discussed the relationship between the tree-ring width index and climatic factors. They found that there were significant differences in the response of the tree-ring width index of Larix chinensis to climatic factors on the southern and northern slopes, and the tree-ring width indices on the northern slopes were more sensitive to temperature factors [10].

It can be seen from the above analysis that the previous studies regarding treeline areas primarily adopted the method of field surveys combined with terrain analyses [10, 16]. Limited by factors such as topography and climate, discrete alpine treeline distribution data present difficulties in reflecting the detailed treeline distribution [17]. With the development of remote sensing technology, multitemporal and multiscale remote sensing data provide an advanced method for fine extraction and dynamic change monitoring of regional alpine treelines. By combining remote sensing with topographic factors, forest line research is more comprehensive and dynamic. However, in the existing research of the Taibai Mountain alpine treeline, the time scales utilized have been either short or more concentrated on one or two specific time nodes where the vegetation response to climate change is not obvious. Based on the above issues, by using high-resolution remote sensing images and elevation data, the dynamic changes in the treeline distribution and its relationship with topographic factors on Taibai Mountain from 1987 to 2020 are systematically analyzed in this study. The response of vegetation to climate change in treeline areas is explored, further providing a basis for mountain ecological restoration and construction. By extending the time scale of monitoring treeline changes, a typical case is provided that illustrates the impact of climate change on a forest ecosystem.

2. Data and Methods

2.1. Overview of the Study Area. Taibai Mountain is located in the middle of the Qinling Mountains and is the primary peak of the Qinling Mountains. Located at the junction of the Zhouzhi, Meixian, and Taibai administrative boundaries (Figure 1), the geographical location of the study area is concentrated at 33° 49′ N–34° 08′ N and 107° 22′ E–107° 52′ E at an altitude of 643–3748 m [10]. The high altitude has significant mountain climate characteristics, and the climates of the northern and southern slopes are significantly different. The northern slopes of the mountains are affected by the climate of the northwest mainland, and this is relatively dry. The average annual rainfall is 500–956 mm, and the average annual temperature is 5.9–7.5°C. The area south of the mountains is affected by the southeast monsoon, and the climate is warm and humid. The annual rainfall is 800–1100 mm, and the average annual temperature is 10.6–14.5°C [16]. The highest altitude of Taibai Mountain is 3771.2 m. The large elevation difference creates a clear vertical climate zone (from a warm temperate zone to a subcold zone) and a vertical vegetation distribution zone (from oak forest, birch forest, and fir forest in Bashan Mountain to Larix chinensis forests and alpine shrub meadows) [9, 18]. Among these, the ecological transition zone between forests and alpine shrub meadows is more obvious, which is typical of an ecologically fragile area, and sensitive to climate change. Therefore, it is an ideal area to study the response of alpine forest lines to climate change.

2.2. Data Collection and Preprocessing. This study is based on Landsat satellite remote sensing images that were utilized to extract the alpine treeline and all data from the United States Geological Survey (USGS) downloaded from the following address: https://glovis.usgs.gov/app. The 30 m resolution images without cloud cover from April to May 1988–2020 were selected, and the specific image types and dates are listed in Table 1. The downloaded Landsat data was processed using a geometric correction and unified projection, and the Taibai Mountain area was cut as a research area to complete the data preprocessing.

The digital elevation model (DEM) raster data was obtained from advanced spaceborne thermal emission and reflection radiometer (ASTER) and global digital elevation model (GDEM) with a spatial resolution of 30 m, and the other pre-treatments, such as reprojection, splicing, and cutting, were performed using ArcGIS. The topographic factors, such as contour, slope, and aspect, were extracted according to the DEM for the extraction of the alpine treeline and the analysis of the influence of topographic factors on their distribution. In addition, the NDVI data were derived from the National Aeronautics and Space Administration (NASA) MOD13Q1 dataset (https://ladsweb.modaps.eosdis.nasa.gov/) for 2000-2020 with a spatial resolution of 250 m and a temporal resolution of 16 d. The MODIS Reprojection Tool (MRT) was utilized to splice and project the downloaded MODIS NDVI data, and then, the maximum synthesis (MVC) method was utilized in ArcGIS to obtain the monthly NDVI data to calculate the annual growing season (April-October) average NDVI.

The meteorological data were derived from the China Meteorological Science Data Sharing Service Network. Nine meteorological stations on Taibai Mountain and its surroundings from 2000 to 2014 and three meteorological stations in Taibai, Liuba, and Chenggu from 2015 to 2019 were selected to obtain the monthly average temperature and monthly accumulated precipitation data to analyze the impact of climate change on the alpine treeline of Taibai Mountain.

2.3. Research Method

2.3.1. Treeline Extraction Based on Supervised Classification. The supervised classification method was used to extract the treeline in this study, and the interest region was selected by visual interpretation combined with the existing research data using ENVI software. There were 50 sample points of shrub meadows, Larix chinensis, Abies fargesii, Betula forest, Quercus forest, and nonforest land selected to quantitatively evaluate the separability of ground object samples and adjust the samples. The maximum likelihood method was selected for the supervised classification, and the wrong or missing pixels were redivided and corrected to obtain the ideal classification
effect by visual interpretation. Second, the mountain top points and contour lines were extracted based on the DEM using GIS software, and the boundary between the forest (primarily focused on *Taxus cuspidata*) and the alpine meadow was extracted as the alpine treeline using a vector topological analysis and superposition analysis [17].

### 2.3.2. Linear Regression Analysis

The least-squares-based linear regression method was used to simulate the dynamic trend of the NDVI, temperature, and precipitation, and the equation is as follows:

\[
\text{NDVI}_{\text{slope}} = \frac{n \times \sum_{i=1}^{n} (i \times \text{NDVI}_i) - (\sum_{i=1}^{n} i)(\sum_{i=1}^{n} \text{NDVI}_i)}{n \times \sum_{i=1}^{n} i^2 - (\sum_{i=1}^{n} i)^2},
\]

where \( n \) represents the years; \( \text{NDVI}_i \) represents the NDVI of the \( i \)th year; and \( \text{NDVI}_{\text{slope}} \) is the trend of the NDVI in \( n \) years. A slope > 0 represents an improvement trend in vegetation in the study area, and slope < 0 represents a degradation trend in vegetation.

### 2.3.3. Correlation Analysis

A correlation analysis was used to study the relationship between vegetation, climatic factors, and topographic factors according to the Pearson correlation analysis method, and the calculation equation is as follows:

\[
r_{xy} = \frac{\sum_{i=1}^{n} [(x_i - \bar{x})(y_i - \bar{y})]}{\sqrt{\sum_{i=1}^{n} (x_i - \bar{x})^2(y_i - \bar{y})^2}},
\]

where \( r_{xy} \) is the correlation between variables \( x \) and \( y \); \( x \) is the NDVI; \( y \) is the meteorological factors including temperature and precipitation; \( x_i \) and \( y_i \) are the \( i \)th year variables; and \( \bar{x} \) and \( \bar{y} \) are the mean values of the variables.

### 2.3.4. Hurst Exponent Analysis

The Hurst exponent was first proposed by the British hydrographer Hurst (1951) to quantitatively describe the sustainability of long-term sequence data. It is widely used in climatology, economics, and other fields [19]. The Hurst exponent is commonly used in climatology and vegetation science to evaluate the persistence of long-term changes.

---

**Figure 1:** The geographical location and meteorological station distribution in the study area.

**Table 1:** Dataset description.

<table>
<thead>
<tr>
<th>Dataset</th>
<th>Collection date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lansat5 TM</td>
<td>1987/4/22</td>
</tr>
<tr>
<td>Lansat7 ETM</td>
<td>2000/05/19</td>
</tr>
<tr>
<td>Landsat5 TM</td>
<td>2011/04/24</td>
</tr>
<tr>
<td>Landsat8 OLI/TIRS</td>
<td>2020/05/02</td>
</tr>
</tbody>
</table>
The NDVI\(_{(t)}\) time-series is:

\[
NDVI\(_{(t)}\) = \frac{1}{\tau} \sum_{i=1}^{\tau} \text{NDVI}_{(t)}(i) \quad (\tau = 1, 2, \ldots, n).
\]  

The cumulative deviation sequence \(X_{(t,r)}\) is:

\[
X_{(t,r)} = \sum_{i=1}^{\tau} (\text{NDVI}_{(t)} - \text{NDVI}_{(t)}) \quad (\tau = 1, 2, \ldots, n).
\]  

The range sequence \(R_{\tau}\) is:

\[
R_{\tau} = \max X_{(t,r)} - \min X_{(t,r)}(1 \leq t \leq r ; \tau = 1, 2, \ldots, n).
\]  

The standard deviation sequence \(S_{(r)}\) is:

\[
S_{(r)} = \left[ \frac{1}{\tau} \sum_{i=1}^{\tau} (\text{NDVI}_{(t)} - \text{NDVI}_{(t)})^2 \right]^{1/2} \quad (\tau = 1, 2, \ldots, n).
\]  

The Hurst exponent is calculated as follows:

\[
\frac{R_{\tau}}{S_{\tau}} = (Ct)^H,
\]  

where \(H\) is the Hurst exponent and \(C\) is the ratio parameter.

Logarithms were taken on both sides of Equation (7), and the least square method was used to fit in the double logarithmic coordinate system \((\ln (R_{\tau}/S_{\tau}), \ln \tau)\) where the slope of the line is the Hurst exponent. When \(0 < H < 0.5\), this indicates that the NDVI time series has antisustainability, and the future trend is opposite to the past. The closer \(H\) is to 0, the stronger the antisustainability is. When \(0.5 < H < 1\), this indicates that past future trends are consistent with past trends, and the greater the \(H\), the stronger the persistence is [20, 21].

3. Results

3.1. Extraction Results and Trends of the Alpine Treeline. It can be seen from Figure 2 that from 1987 to 2020, the treeline of Taibai Mountain showed an overall upward trend, and the average elevation showed a “rising-decreasing” trend, that is, the average elevation of the treeline gradually increased in 1987, 2000, and 2010 and decreased in 2020, but it was still higher than that in 1987. In a comparison of the treeline elevations from 1987 and 2020, it was found that most areas showed an upward trend, and some areas on the south side decreased. The rise of the treeline may have been caused by the invasion of Larix chinenesis into bushes and bare land on the top of the mountain, and the decline of the treeline in some regions may have been due to vegetation degradation caused by climate change. In addition, disturbances, such as mountain fires, windthrow, mountain collapse, and animal destruction, can also cause a decline in the treeline [15].

3.2. Distribution Characteristics of the Alpine Treeline. The alpine treelines in the study area are primarily distributed in the altitude range of 2266-3692 m, as shown in Table 2, and the average elevation is between 3018 and 3063 m. The years of the maximum altitudes of the treeline over the studied periods were ranked as follows: 2000>2010>1987>2020, and the average altitudes were ranked as follows: 2010>2000>2020>1987. The treeline had large elevation spans in 2000 and 2010, with standard deviations of 195 and 193 m, respectively. In 1987 and 2020, the elevation distribution within the upper and lower boundary of the treeline was counted, as shown in Figure 3. The alpine treeline in the study area was most widely distributed in the range of 2950-3250 m, with a cumulative probability of 71.80%. This was consistent with the research results of Beloiu et al. [22]. In the past 34 years, the alpine treeline has shifted from a low altitude to a high altitude. The upward movement of the alpine treeline depends on the supplement of trees outside the treeline, and the influence of climate on the position of the alpine treeline depends on the influence of climate change on the growth of young trees outside the treeline (such as seedlings and young trees) [23]. In addition, some studies have shown that the life stages of alpine trees are different, and the sensitivity to climate change is also different [24]. Therefore, the response of alpine vegetation with different tree ages to climate change will be a direction of future research.

The distribution results of treelines in the different slope ranges are shown in Table 3, where the treelines in the study area are primarily distributed on slopes, abrupt slopes, and steep slopes in the range of 15°-45°, accounting for 91% of the total length. Among them, the range of 25°-35° accounted for the largest proportion, which was 51%. The average elevations of treelines at different slope intervals during the different periods were significantly different. In 2000 and 2010, the average elevations of the treelines in the range of 5°-45° were approximately 3063 m, while those in 1987 and 2020 were relatively low, at 3018 m and 3031 m, respectively. The average elevations of the treelines during different periods were different, and the slope distributions were also different. The maximum values were located on a gentle slope, steep slope, flat slope, and slope in 1987, 2000, 2010, and 2020, respectively. The highest altitude values were primarily concentrated on slopes and steep slopes of 15°-25°.

The maximum and average elevations of the treelines on the eight slope directions were statistically analyzed and are shown in Figure 4. It was found that the elevation of the treeline in each direction was significantly different, and the overall slope tendency was observed. The average and maximum elevations of the treelines had maximum values in the south and southwest directions that were 3078 m (southwest in 2000) and 3652 m (south in 2000), respectively. The minimum values primarily appeared in the north and northwest directions. For example, the average and maximum values of the treelines had minimum values in the northern direction in 1987, and the minimum values appeared in the northwest and northern directions in 2010. The elevations of the Taibai Mountain treeline on the sunny
slopes and semisunny slopes were slightly higher than that on the shady slopes. This was related to the larger areas of the sunny slopes and semisunny slopes in the study area. This was also related to the vegetation types on sunny and shady slopes. Due to the different sunshine hours and intensity of sunny and shady slopes, there were obvious differences in the surface temperature, temperature variation range, evapotranspiration, and soil physical and chemical processes, and the corresponding suitable vegetation types are also different. In addition, the change in the elevation of the treeline in each slope direction directly reflected the "rising-decreasing" trend in the study area over the past 34 years. The average and maximum elevations reached the maximum in 2000 and 2010 and then decreased. Previous studies have shown that, compared with 1988, in 2009, the elevation of shrub meadows, Larix chinensis, Abies fargesii, and oak forests decreased on the sunny slopes and increased on the shady slopes [15].

3.3. Temporal and Spatial Variation Characteristics of the Vegetation. The spatial distribution of the NDVI (Figure 5) showed that the overall vegetation coverage of Taibai Mountain was relatively high, and 88.91% of the regional growing season NDVI was greater than 0.4, which reflected a strong vertical zonality. In the high-altitude areas above the treeline, the vegetation primarily consisted of shrubs, meadows, and nonforest land, and some bare rock areas without vegetation coverage were also included. Hence, the NDVI here was low and less than 0.3. In the middle-low- and middle-high-altitude areas with altitudes of 2000-3000 m, the NDVI was 0.4-0.6, and the vegetation coverage commonly contained oak, birch, and fir forests. The area below 2000 m had the highest NDVI, especially in the altitude range of 1500-2000 m, where the alpine coniferous forest is widely distributed, and the average NDVI was greater than 0.7. The seasonal variation in the NDVI was primarily manifested in the area below the treeline and at an elevation of 2500-3500 m in spring. The vegetation in this area was primarily sensitive to temperature change, and the germination in spring was slightly later than that in the middle and low altitudes. Hence, the NDVI was relatively low. Autumn vegetation withering was more obvious in the middle- and high-altitude areas near the treeline and low-altitude areas below 1000 m.

A linear regression analysis was used to study the spatial variation trend of the vegetation NDVI during the growing season, spring, summer, and autumn of Taibai Mountain from 2000 to 2020. Based on the analysis, Figure 6 shows the spatial distribution of the average NDVI variation trend during the growing season, spring, summer, and autumn. The variation range of the NDVI in each season was small, and the NDVI slope was -0.3-0.3, but the spatial difference was significant. During the growing season, the vegetation on the south slope was dominated by nonindigenous degradation, and the vegetation on the northern low-altitude area was improved. The change trends of the NDVI during spring and autumn were consistent, and there was a
dominate overall improvement that accounted for 86.60% and 77.59%, respectively. The NDVI improvement area on the northern slope was greater than that on the southern slope, and the vegetation improvement trends in the middle and low altitudes were greater than that of the high altitudes. During summer, the NDVI showed the largest area with a degradation trend, and the NDVI had a slope of less than zero. In addition, 37.14% and 3.04% of the regional vegetation NDVI did not change. The increasing trend areas were primarily distributed in the middle- and low-altitude areas in the north with elevations ranging from 1000 to 1500. The NDVI near the alpine treeline showed a slight downward trend during the growing season and spring, but it increased sporadically during summer and autumn. In the

<table>
<thead>
<tr>
<th>Type</th>
<th>Slope range</th>
<th>Average value/m</th>
<th>Maximum value/m</th>
<th>Proportion %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flat slope</td>
<td>0–5°</td>
<td>3016.438</td>
<td>3016.948</td>
<td>0.228</td>
</tr>
<tr>
<td>Gentle slope</td>
<td>5–15°</td>
<td>3018.766</td>
<td>3029.783</td>
<td>8.693</td>
</tr>
<tr>
<td>Slope</td>
<td>15–25°</td>
<td>3018.533</td>
<td>3031.08</td>
<td>26.136</td>
</tr>
<tr>
<td>Abrupt slope</td>
<td>25–35°</td>
<td>3018.567</td>
<td>3031.014</td>
<td>50.955</td>
</tr>
<tr>
<td>Steep slope</td>
<td>35–45°</td>
<td>3018.511</td>
<td>3028.609</td>
<td>13.781</td>
</tr>
<tr>
<td>Dangerous slope</td>
<td>&gt;45°</td>
<td>3004.163</td>
<td>2913.508</td>
<td>0.207</td>
</tr>
</tbody>
</table>

- **Figure 3**: Treeline elevation distribution.
- **Table 3**: Treeline elevation distribution with different slope types.
- **Figure 4**: Treeline elevations on the slopes: (a) average value and (b) peak value.
study area, the primary species above the alpine treeline were shrub meadows, and the primary tree species in the middle- and high-altitude areas were *Abies fargesii*, *Larix chinensis*, birch, and oak forests. Therefore, the vegetation at middle and high altitudes during spring and autumn was significantly improved, and this was consistent with the previous seasonal improvement results of the different vegetation types in the Qinba Mountains found by Zhou et al. [25]. The high-altitude vegetation above the treeline also showed an increasing trend in summer that may have been the result of the transfer of nonforest land to shrub meadows.

3.4. Vegetation Response to Climate Change. The temperature and precipitation during the growing season of Taibai Mountain showed an obvious indigenous growth trend from 2000 to 2019 (Figure 7), and the change rates were 0.06 °C/y and 7.67 mm/y, respectively. The temperature change was small from 2000 to 2012, and the average value ranged from approximately 12°C to 13°C. The temperature rose rapidly after 2012, reached a large value in 2013, dropped significantly in the following two years, and reached the minimum value of 11.50°C during the study period in 2015. The temperature rose rapidly again from 2016 to 2019, reaching a maximum value in 2019. The overall precipitation showed a fluctuating upward trend, and the change was relatively gentle from 2000 to 2016 and increased significantly after 2016. The abrupt change in temperature and precipitation data after 2015 may have been due to the difference in data sources. The meteorological data from 2000 to 2014 came from nine meteorological stations in the study area and its surrounding areas that included Baoji, Zhouzhi, and Taibai. The meteorological data from 2015 to 2019 came from Taibai, Liuba, and Chenggu.

During the past 20 years, the NDVI of the growing seasons had good consistency with the annual variation trend in temperature. However, there was an opposite trend in the NDVI and temperature in 2001, 2017, and 2018; the NDVI of the growing seasons had synchronous increases and decreases. Previous studies have shown that temperature is the primary limiting factor for vegetation growth on Taibai Mountain, and vegetation is more sensitive to temperature change. Therefore, the change in the alpine vegetation coverage can directly reflect the temperature change. The response of the vegetation NDVI to precipitation had a certain lag. In most years, the trend of the NDVI was opposite to the change in precipitation. The NDVI peak corresponded to the valley of precipitation in the graphs, indicating that there was a lag period of approximately one year between the two.

![Figure 5: Spatial patterns of the annual and seasonal NDVI for Taibai Mountain from 2000 to 2020: (a) growing season, (b) spring, (c) summer, and (d) autumn.](image-url)
The growing season mean values of temperature and precipitation (Figures 8(a) and 8(b)), growing season change rate (Figures 8(c) and 8(d)), and the correlation between the two climatic factors and the vegetation NDVI (Figures 8(e) and 8(f)) in the study area from 2000 to 2014 were calculated. Temperature is a climatic factor and the vegetation NDVI (Figures 8(e) and 8(f)) in the study area from 2000 to 2014 were calculated. The correlation coefficients between the NDVI and temperature and precipitation in the growing season of Taibai Mountain were calculated to obtain the spatial distribution of the correlation between the vegetation NDVI and climatic factors. There were obvious spatial differences in the correlation distribution between the temperature and NDVI, and the positive correlation and negative correlation regions accounted for 74.56% and 23.44%, respectively. The southern slope area below the alpine treeline was primarily negatively correlated, and the high-altitude area above the treeline was primarily positively correlated. The NDVI below 1500 m on the north slope was significantly positively correlated with temperature. The increase in temperature limited the growth of vegetation along and below the treeline on the south slope, but it was beneficial to the growth of alpine meadows and shrubs near the ridge line. Due to the long sunshine duration and low water storage capacity of the sunny slopes, the temperature rise increased evapotranspiration and aggravated water stress.

The correlation between precipitation and the NDVI was significantly different at different altitudes, and the positive and negative correlation regions accounted for 67.298% and 31.609%, respectively. In the alpine treeline above 3000 m, an increase in precipitation was conducive to vegetation growth. In the middle- and high-altitude areas of the northern slope area below the alpine treeline was primarily negatively correlated, and the high-altitude area above the treeline was primarily positively correlated. The NDVI below 1500 m on the north slope was significantly positively correlated with temperature. The increase in temperature limited the growth of vegetation along and below the treeline on the south slope, but it was beneficial to the growth of alpine meadows and shrubs near the ridge line. Due to the long sunshine duration and low water storage capacity of the sunny slopes, the temperature rise increased evapotranspiration and aggravated water stress.

The correlation between precipitation and the NDVI was significantly different at different altitudes, and the positive and negative correlation regions accounted for 67.298% and 31.609%, respectively. In the alpine treeline above 3000 m, an increase in precipitation was conducive to vegetation growth. In the middle- and high-altitude areas of the northern slope area below the alpine treeline was primarily negatively correlated, and the high-altitude area above the treeline was primarily positively correlated. The NDVI below 1500 m on the north slope was significantly positively correlated with temperature. The increase in temperature limited the growth of vegetation along and below the treeline on the south slope, but it was beneficial to the growth of alpine meadows and shrubs near the ridge line. Due to the long sunshine duration and low water storage capacity of the sunny slopes, the temperature rise increased evapotranspiration and aggravated water stress.

The correlation between precipitation and the NDVI was significantly different at different altitudes, and the positive and negative correlation regions accounted for 67.298% and 31.609%, respectively. In the alpine treeline above 3000 m, an increase in precipitation was conducive to vegetation growth. In the middle- and high-altitude areas of the northern slope area below the alpine treeline was primarily negatively correlated, and the high-altitude area above the treeline was primarily positively correlated. The NDVI below 1500 m on the north slope was significantly positively correlated with temperature. The increase in temperature limited the growth of vegetation along and below the treeline on the south slope, but it was beneficial to the growth of alpine meadows and shrubs near the ridge line. Due to the long sunshine duration and low water storage capacity of the sunny slopes, the temperature rise increased evapotranspiration and aggravated water stress.
2000-3000 m, precipitation and the NDVI were significantly negatively correlated, and the negative correlation area on the south slope was significantly greater than that on the north slope. In the middle- and low-altitude areas below 1500 m on the south and north sides of the study area, the NDVI was significantly positively correlated with precipitation. This result indicated that an increase in precipitation in these areas had a promoting effect on the vegetation growth. Within the treeline range, the temperature and precipitation were positively correlated with the vegetation NDVI, but an increase in temperature was not conducive to vegetation growth on the south slope. The positive response of vegetation to temperature and precipitation in the low-altitude areas was more obvious. Trees in high-altitude areas were more sensitive to temperature, while trees in low-altitude areas were typically more sensitive to precipitation and water availability during the growing season. Similar findings were found for the Qinling and central Hengduan Mountains [8, 26].

3.5. Future Trends of the Vegetation Dynamics. Based on the Hurst exponent analysis, the sustainability of the NDVI change of Taibai Mountain was calculated, and the spatial distribution of the Hurst exponent (Figure 9(a)) was obtained. In addition, the NDVI trend during the growing season and the Hurst exponent were coupled to analyze the spatial
distribution of future vegetation sustainability changes (Figure 9(b)). I denotes sustainable and substantial amelioration; II denotes sustainable and slight amelioration; III denotes unsustainable and from degradation to amelioration; IV denotes unsustainable and from amelioration to degradation; V denotes sustainable and slight degradation; and VI denotes sustainable and substantial degradation. The area with anti-persistent change ($0 < \text{Hurst} < 0.5$) in the vegetation cover of Taibai Mountain was larger than that with persistent change ($0 < \text{Hurst} < 1$), accounting for 67.36% and 31.52% of the total area, respectively. The area with uncertain change was 1.12%. The future trend was primarily improved, and the improvement area and degradation area accounted for 81.35% and 18.66%, respectively. Among them, the sustainable significant improvement area was 1.52%, which was distributed in the middle- and low-altitude areas in the northeast of the study area. The unsustainable improvement area accounted for the largest proportion at 56.64% of the total area. Vegetation degradation was found to be primarily unsustainable in the future and was primarily concentrated near the
alpine treeline on the northern slopes. The persistent degradation area accounted for a relatively small proportion at only 0.89%, and it was scattered sporadically in the high-altitude areas.

4. Conclusions

This study extracted alpine treelines from 30 m resolution Landsat remote sensing data obtained from 1987, 2000, 2010, and 2020. The dynamic changes in vegetation near the treeline in the recent 21 years and its response to climate change were analyzed. The relevant research results will help us to understand the response of forest ecosystems to climate change correctly and provide a theoretical basis and data support for the protection and construction of mountain ecological systems. The following are the primary conclusions of this study:

(1) The elevation distribution range of the treelines of Taibai Mountain was 2266-3692 m, and 71.80% of the treelines were distributed in the range of 2950-3250 m. The alpine treelines were primarily distributed on slopes, abrupt slopes, and steep slopes of 15-45°, with the largest proportion in the range of 25-35°. The southern and southwest slopes had the highest elevations, and the northern slopes had the lowest elevations. In the past 34 years, the alpine treelines of Taibai Mountain showed a trend of "rising-decreasing" that declined in 2020, but the average altitude was still higher than that in 1987, with the altitude of the treelines showed an upward trend as a whole.

(2) The spatial distribution of the vegetation NDVI had a vertical zonality and showed an increasing trend. The improved areas during spring and autumn were greater than 77%, and the vegetation at the middle and high altitudes was significantly improved. The degraded area was the largest during summer, but the high-altitude vegetation above the treeline also showed a trend of improvement. This resulted in some nonforest land being transferred to shrub meadows. In the future, 56.64% of the regional vegetation will not continue to improve, and there is a risk of sustainable degradation in some areas on the northern side of the treeline.

(3) Forest vegetation was more sensitive to temperature change. The NDVI during the growing season was consistent with the trend of temperature increase and decrease, and the response of the vegetation NDVI to precipitation had a certain hysteresis. During the growing season, vegetation was primarily positively correlated with temperature and precipitation. On the southern slopes below the treeline, an increase in temperature will inhibit vegetation growth, while the temperatures on the northern slopes were not significantly positively correlated with the vegetation NDVI. The correlation between the precipitation and vegetation NDVI was significantly affected by topography, and the correlation was primarily negative at the middle and high altitudes. The middle and low altitudes below 1500 m were significantly positively correlated. A warm and humid climate was found to be conducive to vegetation growth above the treeline.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.
Acknowledgments

This work was supported by the Innovation and Entrepreneurship Training Program for College Students (grant number 202110697036).

References


