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Influence of Anthropogenic Activities and Major Natural Factors on Vegetation Changes in Global Alpine Regions

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Abstract: Understanding vegetation changes and their driving forces in global alpine areas is critical in the context of climate change. We aimed to reveal the changing trend in global alpine vegetation from 1981 to 2015 using the least squares regression method and Mann-Kendall (MK) test. The area-of-influence dominated by anthropogenic activity and natural factors was determined in an area with significant vegetation change by residual analysis; the primary driving force of vegetation change in the area-of-influence dominated by natural factors was identified using the partial correlation method. The results showed that (1) the vegetation in the global alpine area exhibited a browning trend from 1981 to 2015 on the annual scale; however, a greening trend was observed from May to July on the month scale. (2) The influence of natural factors was greater than that of anthropogenic activities, and the positive impact of natural factors was greater than the negative impact. (3) Among the factors that were often considered as the main natural factors, the contribution of albedo to significant changes in vegetation were greater than that of temperature, precipitation, soil moisture, and sunshine duration. This study provides a scientific basis for the protection of vegetation and sustainable development in alpine regions.

Keywords: global change; normalized difference vegetation index; alpine vegetation; anthropogenic activity; climate change; natural factors

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1. Introduction

Alpine vegetation is an essential component of terrestrial ecosystems [1]; it can maintain the local climate and improve local economy [2]. Therefore, the degradation and conservation of alpine vegetation is important ecologically, socially, and for sustainable development problems [3]. Currently, many governments and international organizations, including the United States, are paying increased attention to alpine vegetation [4,5]. The present study on global alpine vegetation change will help enhance our understanding of alpine ecosystem responses to global warming, formulate corresponding protection measures, and contribute to regional sustainable development.

The vegetation in alpine areas is considerably sensitive to natural factors and anthropogenic activity [6]. These areas are characterized by a short growing season, high altitude, cold temperatures, and poor environmental conditions [7]. Hence, alpine vegetation is very sensitive to climate change, particularly to increases in temperature [8]. Previous studies have shown that natural factors, such as temperature or precipitation, are the main cause of vegetation change in some alpine areas [8]. Climate-induced warming of the near-surface atmosphere, and the corresponding rise in surface temperature, will result in significant changes in the water and energy balance of permafrost areas, leading to changes in vegetation [9]. In addition, anthropogenic activities have a significant impact on alpine vegetation [10], including livestock grazing and tourism [11]. With economic development and the increase in material demand, the strain of grazing on vegetation increases daily [12]. Furthermore, rapid population growth and engineering projects (especially the construction and operation of engineering infrastructure) have changed the original surface conditions and contributed to the degradation of the ecological environment [9]. In alpine regions that provide recreational and tourism opportunities, tourists and pack animals (often used to transport equipment) damage sensitive vegetation [13].

The factors influencing alpine meadow and grassland areas in most parts of the world have been identified. The ground surface temperature and soil moisture were the most important explanatory variables of plant community composition in the Western Swiss Alps [14]. Precipitation may be the dominant driver in the alpine grassland distribution on the Tibetan Plateau [15]. The combination of climate, soil, animal grazing, and agricultural practices affect the alpine grasslands in eastern Italy [16]. However, it has not been determined which anthropogenic activities and natural factors mainly affect alpine vegetation change on a global scale.

Therefore, in this study, we examined the response of global alpine vegetation to anthropogenic activities and major natural factors from 1981 to 2015. This was achieved in three steps: (1) the identification of areas of significant changes in global alpine vegetation, (2) analysis of the areas where anthropogenic activities and major natural factors cause significant changes in alpine vegetation, and (3) identification of the most important driving factor in the area where the main natural factors cause significant changes in vegetation.

2. Data

The data we used included major natural factors, land use, and alpine data, and the normalized difference vegetation index (NDVI) (Table 1). We used linear interpolation to unify the data resolution to 0.25°.

2.1. NDVI

The NDVI data adopted the global GIMMS NDVI. The spatial resolution of the data was 1/12°, and the temporal resolution was 16 days. We used the maximum synthesis method to obtain the monthly NDVI value and resampled it to 0.25°.

2.2. Natural Factors

We analyzed the factors affecting vegetation change using natural factors that are typically considered as key determinants, including temperature, precision, soil movement, albedo, and sunshine duration [17,18]. The source of these data is the ERA dataset [18]. The spatial resolution of temperature, precipitation, and soil moisture was 0.25°, and the spatial resolution of albedo and sunshine duration was 0.75°. We unified the data resolution to 0.25° by resampling.

2.3. Land Use

We used the Moderate Resolution Imaging Spectroradiometer (MODIS) land cover type product (MCD12C1) from 2000–2015, with a spatial resolution of 0.5°. Land use types were divided into 17 categories in this dataset. The vegetation area was defined as vegetation that did not change from 2000 to 2015.

2.4. Alpine Regions

We used the alpine region boundary studied by Testolin, et al. [19]. The regions are the areas above the actual regional tree line [20]. The data were drawn on Google Earth Engine platform using satellite images with a spatial resolution of 30 m, based on the elevation of the regional tree line to study the regional changes in alpine vegetation.

Table 1. Remote sensing vegetation and natural factors data from 1981 to 2015.

Category	Index	Spatial Resolution	Time Resolution	References
GIMMS NDVI	NDVI	1/12°	Half a month	Eastman, et al. [21]
ERA	Temperature	0.25°	One month	Zhang, et al. [22]
	Precipitation	0.25°	One month	Guan, Lu, Yin, Xue, Jiang, Kang, He and Heiskanen [17]
	Soil Moisture	0.25°	One month	Li, et al. [23]
	Albedo	0.75°	One month	Li, et al. [24]
	Sunshine Duration	0.75°	One month	Wang, Fan, Frappart, Ciais, Sun, Liu, Li, Liu, Moisy and Wigneron [18]
MODIS land cover type product	Vegetation	0.5°	One year	Chen, et al. [25]
Alpine regions	Alpine regions	30 m	-	Testolin, Attorre and Jimenez-Alfaro [19]

3. Methods

3.1. NDVI Trend Analysis

We used the ordinary least squares (OLS) model to analyze the monthly variation trend of NDVI from 1981 to 2015, and the Mann-Kendall (MK) test to assess significance. This method can accurately identify areas with significant changes in vegetation [25]. The formula of OLS is as follows [20,26]:

$$y_i = N_0 + N_i(x_i) + \varepsilon \quad (1)$$

where y_i = dependent variable (NDVI), N_0 = intercept, N_i = estimated coefficient, x_i = independent variable (temperature, precipitation, soil moisture, albedo, and sunshine duration), ε = error.

3.2. Identification of Areas Significantly Affected by Anthropogenic Activities

We used residual analysis to calculate the impact of anthropogenic activities and natural factors on monthly variations in NDVI. Based on the multiple linear regression method, we predicted the monthly NDVI variation trend under the influence of natural factors and determined the impact of anthropogenic activities by calculating the difference between the predicted and actual NDVI values [27]. The formula is as follows [28]:

$$NDVI_{res} = NDVI_{obs} - NDVI_{pre} \quad (2)$$

where $NDVI_{pre}$ is the predicted value of NDVI, $NDVI_{obs}$ is the observed NDVI values, and $NDVI_{res}$ is the residual values of NDVI. The dominant factors are judged according to the relative contributions of anthropogenic activities and natural factors [27] (Table 2).

Table 2. Determination of dominant factors of anthropogenic activities and natural factors on vegetation.

$Slope_{OB}$	Driver	Driver Division		Contribution Rate (%)	
		$Slope_{NI}$	$Slope_{AI}$	NI	AI
>0	NI & AI	>0	>0	$Slope_{NI}/Slope_{OB}$	$Slope_{AI}/Slope_{OB}$
	NI	>0	<0	100	0
	AI	<0	>0	0	100
<0	NI & AI	<0	<0	$Slope_{NI}/Slope_{OB}$	$Slope_{AI}/Slope_{OB}$
	NI	<0	>0	100	0
	AI	>0	<0	0	100

OB = predicted NDVI; NI = influence of natural factors; AI = influence of anthropogenic activities.

3.3. Identification of Main Natural Factors in Areas Significantly Affected by Natural Factors

We used a partial correlation analysis to determine the dominant factors affecting vegetation in the natural environment. This method revealed the dominant natural factors influencing monthly NDVI variations [29]. The formula is as follows [30]:

$$P_{abc} = (P_{ab} - P_{ac}P_{bc})/(\sqrt{(1 - P_{ac})^2}\sqrt{(1 - P_{bc})^2}) \quad (3)$$

where x, y, and z represent three factors. P_{abc} is the correlation between factors x and y after the interference associated with factor z is excluded. P_{ab} reflects the linear correlation coefficient between factors x and y, and P_{ac} and P_{bc} have similar meanings.

4. Results

4.1. Monthly Variation Trend of NDVI

The vegetation area accounts for about 67% of the alpine regions. The vegetation is primarily distributed in North America, South America, and Asia. The vegetation in the alpine area showed an overall browning trend from 1981 to 2015 (Figure 1). However, a greening trend was observed from May to July, every year during this period in the alpine regions. The proportions of regions with substantial monthly changes in vegetation were considerably different (Figure 2). Between January and April, the area with a significant change in vegetation was smaller. The lowest change proportion was in January (17%), and the highest was in September (65%). There was a difference between the months in which large areas of significant greening and browning in the alpine regions. Among the significant greening areas, the area of vegetation with significant greening from May to July accounts for the largest proportion (35–50%) of the area of vegetation in alpine areas, and the highest in June. The proportion of significant greening in other months is low (<10%), of which September is the lowest (2%). Among the significant browning area, the area of vegetation with significant browning from September to November accounts for the largest proportion (48–63%) of the vegetation area in alpine regions, and the highest in September. The proportion of significant greening in other months is low (<33%), and the lowest in May (9%).

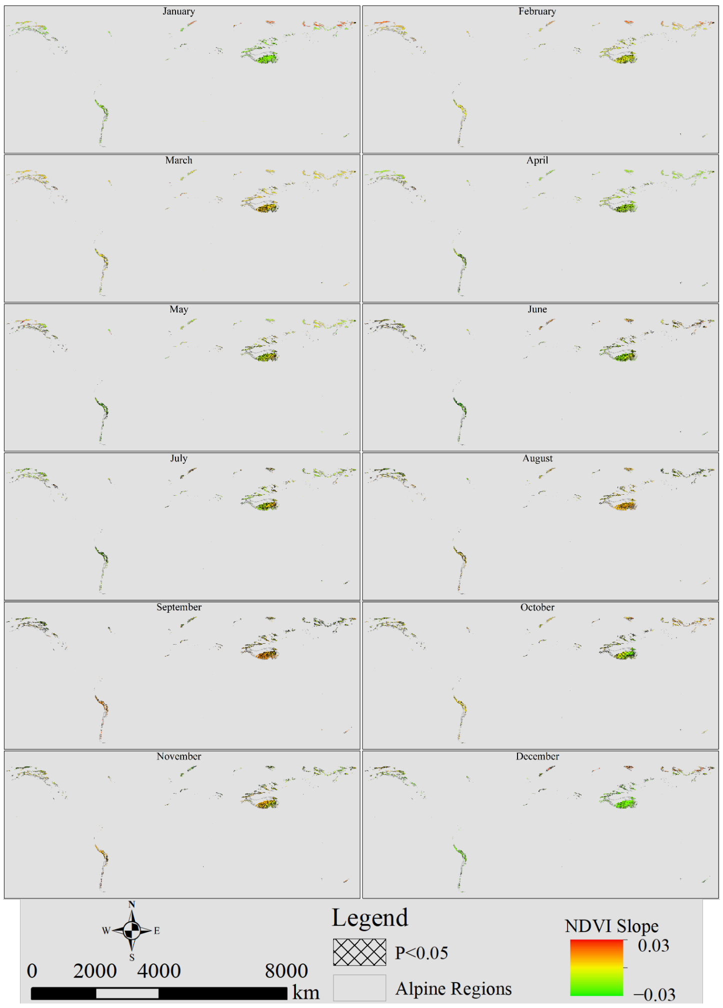

Figure 1. Vegetation change trend of global alpine regions from 1981 to 2015.

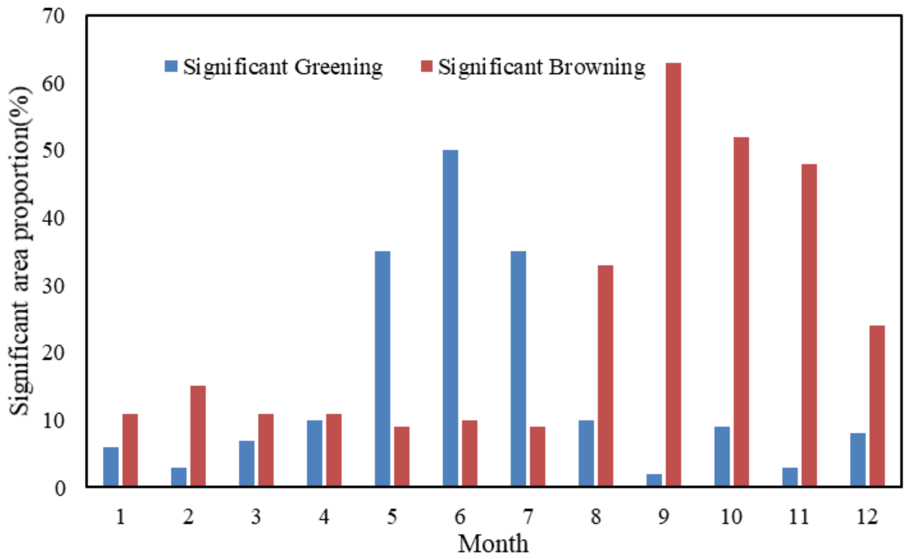

Figure 2. Significant change area proportion of global alpine regions vegetation from 1981 to 2015.

4.2. Contribution of Anthropogenic Activities and Major Natural Factors to Areas with Significant Vegetation Changes

The areas with significant vegetation greening change ($p < 0.05$) caused by major natural factors were greater than the sum of the significant vegetation browning change caused by anthropogenic activities and the significant change in vegetation caused by natural factors, except in April, June, and July (Figure 3 and Supplementary Figure S1).

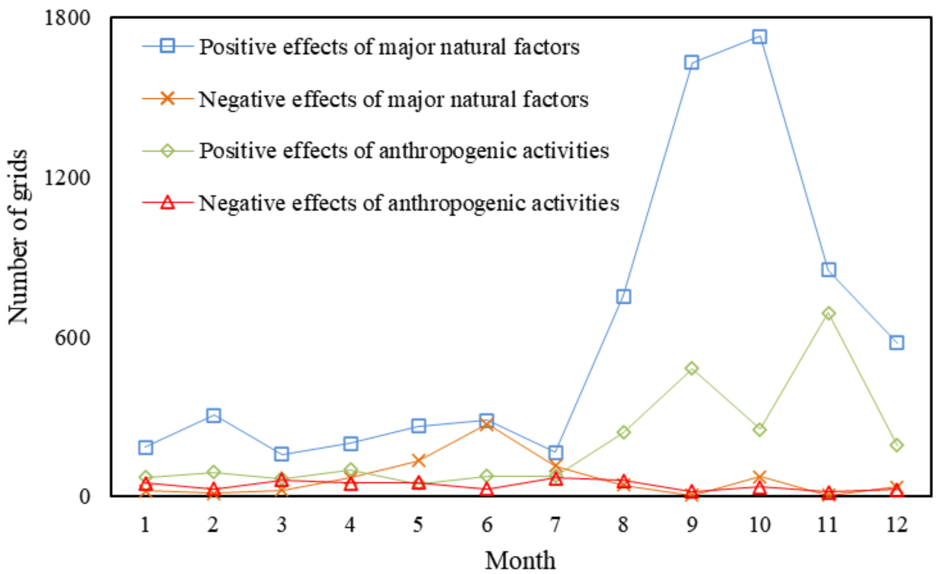

Figure 3. Number of grids with significant changes in vegetation caused by anthropogenic activities and major natural factors.

The area of significant vegetation greening caused by major natural factors accounted for more than 51% of the area of significant vegetation changes caused by major natural factors in each month. Among them, its accounted for the highest proportion in September and November. In addition, the area causing significant browning of vegetation accounted for the highest (49%) in June.

The area of vegetation significantly greening caused by human activities accounted for more than the area of vegetation significantly browning caused by human activities in other months except May. Among them, the area causing significant greening of vegetation accounted for the highest in September and November. In addition, the area causing significant browning of vegetation accounted for the highest in March and May.

The impact of anthropogenic activities and the main natural factors on the significant changes in vegetation vary significantly in the different months (Supplementary Table S1). From September to November, the areas of significant changes in vegetation caused by anthropogenic activities and natural factors accounted for 71–78%, whereas they accounted for only 22–26% from May to July.

4.3. Dominant Factors Causing Significant Changes in Vegetation in the Major Natural Factors

The percentages of the five natural factors significantly affecting ($p < 0.05$) significant vegetation greening and browning ($p < 0.05$) were calculated for alpine regions (Figure 4). The major natural factors could not reveal the primary influences causing significant changes in alpine vegetation every month. The percentage area with significant vegetation greening change caused by the major natural factors was relatively larger from September to November (66–86%). The percentage area with significant vegetation browning change caused by the major natural factors was relatively larger from October to November (56–57%).

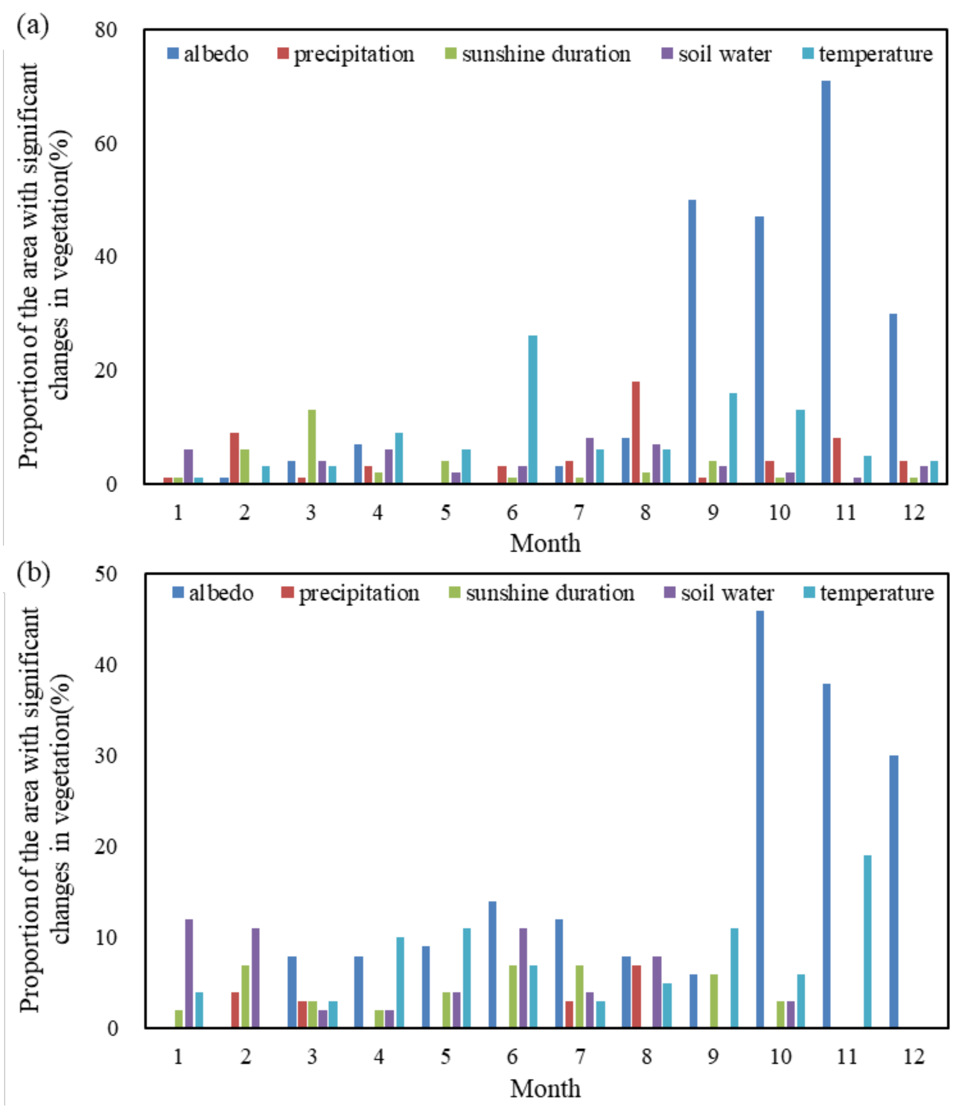

Figure 4. The proportion of the area with significant changes in vegetation caused by the major natural factors, positive impacts (**a**), and negative impacts (**b**).

The influence of the major natural factors was different every month. For significant vegetation greening changes, the major natural factor in January and July was soil moisture, whereas during February and August it was precipitation. Sunshine duration, temperature, and albedo were the major natural factors during March, April to June, and September to December, respectively. For significant vegetation browning changes, soil moisture was the major natural factor during January to February and August. Albedo was the major natural factor during March, June to August, and October to December and temperature was the major natural factor during April to May and September.

5. Discussion

5.1. Variation Trend of Vegetation in Alpine Vegetation

The vegetation in the alpine regions showed a browning trend, contrary to the global trend of vegetation change. Previous studies have rarely revealed the vegetation changes in global alpine regions. Although studies have revealed global vegetation changes [31,32]. However, at different spatial scales, the trend of vegetation change and its influencing factors are different. A previous study identified long-term greening trends in global vegetation, with a significant increase in vegetation greening exceeding 45% of the interannual variability compared with a decrease of 21% [25]. However, we observed that vegetation in alpine regions showed a tendency for browning on the annual scale, and the significant browning areas were larger than the significant greening areas in months 1–4 and 8–9 as shown in Figure 2. In addition, we found that vegetation generally showed a greening trend from months 5 to 7. This result was directly related to the main distribution of vegetation in alpine regions. Since the vegetation in alpine areas was mainly distributed in North America and Asia. May to July is the month of rapid growth of vegetation both alpine areas and other areas in the northern hemisphere [33–35]. In addition, the vegetation greening speed in the northern temperate zone (25–50° N) was faster than that in the high latitudes (>50° N) since 2000 [36,37]. Therefore, the vegetation significant greening area was larger than browning in months 5 to 7.

5.2. What Is the Dominant Factor Causing Significant Changes in Alpine Vegetation?

The impact of the major natural factors on alpine vegetation was greater than that of anthropogenic activities. The positive impact of the major natural factors was greater than the sum of the negative impact and the overall impact of the anthropogenic activities except during April, June, and July. It was a global consensus that global vegetation is more affected by anthropogenic activities than by natural factors [38]; however, in our study we found that the opposite was true in the alpine regions. This was due to fewer residents in alpine areas. In addition, because of the landform and climate conditions, most human activities were difficult to carry out [39]. Therefore, the influence of natural factors is greater than that of human activities. Meanwhile, the positive influence of natural factors is greater than the negative influence in every month. This may be because alpine ecosystems are particularly sensitive to climate warming their biota is generally limited by low temperatures [40].

The positive impact of anthropogenic activities was greater than that of the negative impact on the annual scale. The significant greening area of vegetation caused by human activities is more than the significant browning area of vegetation caused by human activities in other months except May. The significant greening area of vegetation caused by human activities is more than the significant browning area of vegetation caused by human activities in other months except May. Among them, the months which the highest area of significant greening of vegetation were September and November. This indicates that people and government in all the alpine regions around the globe attach great importance to vegetation protection in these regions, especially in September and November. Previous studies infrequently revealed the influencing factors of global alpine vegetation; thus, we believe that the positive impact of anthropogenic activities in alpine areas is due to the effect of CO_2 fertilization [32]. In addition, the high mountainous areas were predominantly permafrost, and anthropogenic activities, such as the construction of the Qinghai Tibet railway, have promoted an influx of residents and tourists, resulting in the thawing of the permafrost and the greening of vegetation in alpine areas [9]. The negative effects of anthropogenic activities on alpine vegetation came primarily from grazing and tourism [41]. Furthermore, it is highest in March and May. Since the vegetation in alpine areas is mostly grassland and meadow, and the main sources of income for the local economy are grazing and tourism [11]. Therefore, vegetation browning in alpine areas was partly attributable to local economic development.

5.3. Which of the Natural Factors Contribute the Most?

Often the natural factors applied as major factors in revealing vegetation changes in global alpine regions, do not act as major drivers in every month, such as temperature, precipitation, soil moisture. After deducting the areas with significant changes caused by anthropogenic activities, we believe that the significant changes in vegetation in the remaining areas were all caused by natural factors. In these areas, the major natural factors that were chosen for this study only led the significant green area percentage of vegetation to exceed 50% from September to November and the significant brown area percentage of vegetation to exceed 50% from October to November.

The primary drivers of vegetation change varied by month. The main driving forces of the areas with significant greening and browning were different. Among the natural factors, global warming is thought to be the main driver affecting vegetation growth [42] and is generally considered the main driver of vegetation change in alpine regions [43]; for example, low temperatures increase the risk of grassland degradation [44]. However, regarding the length of the month, the areas with significantly green vegetation where albedo was used as the major natural factor, revealed vegetation changes over four months (September to December), which was greater than that of temperature (three months), precipitation, and soil moisture (two months). In areas with significant vegetation browning, albedo (as the major natural factor) could reveal vegetation changes over 7 months (months 3, 6–8, 10–12; Figure 3), which was greater than that of temperature and soil moisture (3 months). Therefore, from the perspective of duration, albedo was the most important of these major natural factors.

The main driver of vegetation change in alpine regions was spatial heterogeneity. Previous studies have demonstrated that the major drivers of global vegetation change are spatially heterogeneous [42]; we also found this to be the case in alpine regions. This was due to the differences in management policies and vegetation types in various countries. For example, grassland greening in the Qinghai-Tibet Plateau is controlled by precipitation and sunshine duration [45,46]. The vegetation NDVI in the Qinling Mountains is strongly correlated with temperature, and the sensitivity of different vegetation types to temperature is inconsistent [47]. Vegetation in northwestern North America is affected by early summer warming [48], and vegetation in the northeastern Greater Caucasus of Azerbaijan is affected by a combination of temperature and precipitation [11].

5.4. Limitations

This study adopted five major influencing factors that are typically used to study greening and browning of vegetation. These factors were temperature, precipitation, soil moisture, albedo, and sunshine duration [17,18]. Our results showed that the positive impacts of anthropogenic activities were greater than the sum of the negative impacts, and those of the major natural factors in regions where global alpine vegetation underwent significant changes. In addition, vegetation showed a browning trend in global alpine areas, suggesting that there are other natural factors that have yet to be revealed. The impacts of anthropogenic activity and climate change were exposed through the methodology used in this study. Furthermore, we found the limitations of current natural factors in illuminating the factors influencing vegetation change. This study provides a scientific basis for vegetation dynamics and sustainable development in alpine regions.

6. Conclusions

In this study, the least squares regression method and MK test were used to reveal the changing global alpine vegetation trend from 1981 to 2015. In the areas with significant vegetation change, the influences of anthropogenic and natural factors were determined using residual analysis. Moreover, the main driving force in the area-of-influence dominated by natural factors was identified using the partial correlation method. The following conclusions were drawn:

(1) Global alpine vegetation exhibited an overall browning trend from 1981 to 2015. However, a green trend was present during May-July during this period.
(2) The considerable impact of the major natural factors on alpine region vegetation were greater than that of anthropogenic activities, and the positive impact of these natural factors was greater than the negative impact. However, anthropogenic activities had a greater impact on vegetation browning than the major natural factors during months 1, 3, 8, 9, and 11.
(3) The contribution of albedo to significant changes in vegetation was greater than that of the other major natural factors.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/land11071084/s1, Figure S1: The residual analysis of anthropogenic activities and natural impacts in global alpine regions; Table S1: Number of grids with significant changes in vegetation caused by anthropogenic activities and major natural factors.

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