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Variations and controlling factors of vegetation dynamics on the Qingzang Plateau of China over the recent 20 years

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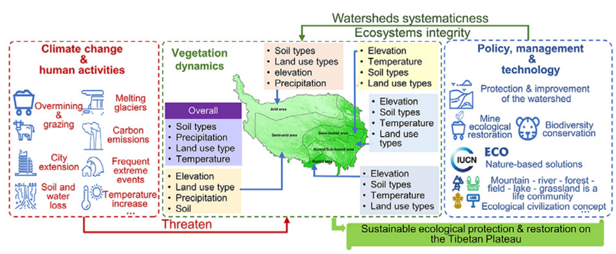
HIGHLIGHTS

- NDVI decreased gradually from southeast to northwest of the Qingzang Plateau.
- Overall NDVI increased 0.02 per year from 1998 to 2018 on the Qingzang Plateau.
- Variables showed enhanced interaction especially between altitude and slope.
- Land use affected vegetation distribution especially in arid and semi-arid areas.

GRAPHICAL ABSTRACT



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ABSTRACT

The impacts of climate change and human activities on vegetation dynamics have attracted wide attention, especially in sensitive and vulnerable areas such as the Qingzang Plateau of China. In this region, a series of ecological restoration projects have been launched while the effectiveness of these projects requires evaluation and further improvements. Remote sensing with high temporal resolution and spatial coverage is an effective way for the vegetation dynamics research in this region. In this study, the spatial and temporal distribution of climate factors and vegetation coverage as well as the influencing factors such as air temperature, precipitation, land use, slope, slope direction, soil and altitude were analyzed. The geographical detector was used to analyze the influence of climate factors on vegetation coverage and the interaction among factors in different eco-geographical regions. The results showed that: 1) the average values from the 20 years of normalized difference vegetation index (NDVI) decreased gradually from southeast (> 0.61) to northwest (0.12). The overall average of NDVI increased 0.02 per year from 1998 to 2018 and the impact factors varied among different eco-geographical regions; 2) some controlling factors showed nonlinear enhancement such as altitude and slope; 3) land use was an important factor affecting the distribution of vegetation especially in humid, semi-arid and arid areas, but the impacts of elevation and temperature were stronger than land use types in semi-humid and humid areas. The design and construction of ecological protection and restoration projects on the Qingzang Plateau required scientific and detailed demonstration as well as monitoring and evaluation. In addition, new tools and theories were also needed in the selection of ecosystem restoration strategies. Based on the findings, this study also provides suggestions for the sustainable ecological restoration on the Qingzang Plateau.

1. Introduction

The impacts of climate change on global vegetation growth have been extensively studied (Parmesan and Yohe, 2003; Wang et al., 2019a). Terrestrial ecosystems and climate factors interact with each other through the carbon-water-energy cycle at the interface of land and atmosphere (Lanning et al., 2019). According to the Intergovernmental Panel on Climate Change (IPCC) assessment report, temperature and precipitation will increase in temperate regions in the future, while warming and drying trends may occur in mid-latitude parts of the Northern Hemisphere (Pachauri and Reisinger, 2007; Stocker et al., 2013b; Qin et al., 2014). These changes will threaten the sustained

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vegetation growth. Human activities aggravate the impact of climate change (Wu, 2019). On the one hand, vegetation restoration increases its coverage through the plantation of trees and the conversion of farmland to shrublands/forests; on the other hand, human activities such as urban expansion and high-intensity grazing aggravate vegetation degradation (Sagan et al., 1979; Piao et al., 2007; Bonan, 2016; Bastin et al., 2019; Chen et al., 2019; Stovall et al., 2019; Luo et al., 2020). To make a useful model for global restoration, the Government of Germany launched a practice named the *Bonn Challenge* together with the International Union for Conservation of Nature (IUCN). This was followed by the United Nations General Assembly, which proclaimed 2021–2030 as the *Decade on Ecosystem Restoration*. This period is also the last decade of *Protection and Construction Planning of Ecological Security Barrier in Qingzang Plateau (2008–2030)*.

The Qingzang Plateau is an important ecological security barrier of Asia (Yao, 2014; Yao et al., 2017; Yao et al., 2019). Although total vegetation coverage has increased in China, the increase rate on the Qingzang Plateau is lower than that in other places, with some central regions even showing an obvious decreasing trend (Wang et al., 2019a). Due to the special alpine environment, this region is highly sensitive to climate change, and the growing temperature rate is higher than the global average (Bajracharya et al., 2015; Piao et al., 2019). A series of changes have taken place in vegetation characteristics to adapt to the high elevation, cold and high radiation (Dolezal et al., 2016; Mishra and Mainali, 2017; Keenan and Riley, 2018; Anderson et al., 2020; Li et al., 2020; Wang et al., 2020). In the past few decades, changes in temperature, precipitation, radiation and human activities on the Qingzang Plateau have had significant impacts on plant photosynthesis, respiration, water use efficiency, element content, spatial distribution of vegetation, phenology, community composition and biodiversity, and ecosystem services (Gao et al., 2008; Ge et al., 2012; Hao et al., 2012; Guo et al., 2017; Alhassan et al., 2018; Cui et al., 2018; Guo et al., 2019; Ma et al., 2019). At the same time, vegetation has a feedback on climate change through changes in surface roughness and albedo, and also has a significant influence on regional soil characteristics through, for example, surface cover and root growth (Sagan et al., 1979; Cui et al., 2012; Hou et al., 2016).

The complex landforms and low oxygen content make field work challenging on the Qingzang Plateau. In such case, remote sensing has become an effective mean of large-scale research in this area (Zhang et al., 2007; Liu et al., 2014; An et al., 2018). There are widely used indices that can reflect vegetation characteristics such as leaf area index (LAI), normalized difference vegetation index (NDVI), ratio vegetation index (RVI), and difference vegetation index (DVI) (Zhu et al., 2012; Qiu et al., 2013; Liang et al., 2014; Wu et al., 2017). NDVI can be influenced by factors such as soil reflectance, wet ground, snow, dead leaves and roughness. There are multiple types of NDVI data source such as AVHRR NDVI, SPOT/VEGETATION NDVI and MODIS NDVI (Zhu et al., 2012; Qiu et al., 2013; Liu et al., 2015; Wang et al., 2019a). Among them, SPOT/VEGETATION NDVI has high resolution and sensitivity, based on the optical multi-spectral instrument that performs daily, and almost complete, cover of the Earth with 1 km^2 spatial resolution with four spectral bands (Gouveia et al., 2010; Liu et al., 2015).

In recent years, the interaction between the controlling factors of vegetation dynamics has attracted wide attention, and many methods are continuously developing to quantify the contribution of the controlling factors and their interactions (Wang et al., 2016). Geographic detector (geo-detector) is a new statistical method to detect spatial differentiation and identify the controlling factors, which has no linear assumption, concise form and clear physical meaning (Wang and Xu, 2017). This method can be used to measure spatial differentiation, detect and explain factors, and analyze the interaction between variables, which has been applied in many fields of natural and social sciences (Wang and Hu, 2012; Wang et al., 2016).

A series of results have been obtained in the study of spatial distribution and controlling factors of the Qingzang Plateau vegetation based on remote sensing. Existing studies showed that changes of climate elements such as temperature, precipitation and radiation have impacts on vegetation physiological characteristics, such as photosynthesis, respiration, water use efficiency and element content, as well as ecological characteristics, such as vegetation spatial distribution and species composition (An et al., 2018; Anderson et al., 2020; Piao et al., 2019). The land use changes also impact the vegetation, for example, the conversion from forest or grassland to farm or construction land could decrease the vegetation coverage (Fan et al., 2010; Piao et al., 2007). While only few studies considered the combined interaction effect of climate and land use types, and the comparison between different regions and across different scales still needs further investigation. This study focuses on eco-geographical regions, analyze the vegetation dynamics and its controlling factors on the Qingzang Plateau from 1998 to 2018 by using SPOT/VEGETATION NDVI, meteorological data, and the geo-detector model. This study aims to: 1) analyze spatial and temporal variation of vegetation coverage in recent 20 years on the Qingzang Plateau; 2) identify the main controlling factors of vegetation coverage changes and their interactions in different eco-geographical regions; and 3) provide suggestions for the sustainable ecological restoration on the Qingzang Plateau.

2. Data & Methods

2.1. Description of the sites

Qingzang Plateau (78.3°–103.1° E, 26.5°–39.5° N) is located in the southwest part of China (Fig. 1). It occupies an area of about 2.5×10^6 km^2 with an average elevation of more than 4,000 m (Yao et al., 2017). This region is the central part of Asia and the water source of several important rivers, and is also regarded as an ecological security barrier (Fan et al., 2010; Chen et al., 2012; Yao et al., 2019).

The region is mainly affected by the South Asian monsoon. The annual average temperature in most parts is below 0°C, but the annual average temperature in the southeastern low-altitude part is above 10°C. Extremely high solar radiation lead to extremely high evaporation, while the average annual precipitation varies from more than 1000 mm in the southeast to less than 50 mm in the northwest, and an extremely uneven seasonal distribution. The land cover is mainly grassland. Alpine grassland is the most widely distributed and the largest grassland types (Cui et al., 2020). In addition, some parts of the Qingzang Plateau are covered with rare virgin forests (Cheng et al., 2018; Li et al., 2018a).

2.2. Data

Annual NDVI data were based on SPOT/VEGETATION NDVI with maximum value composite (MVC) (Liu et al., 2015). The time range of the NDVI data set was from January 1998 to December 2018, and it was a time series data set with 10 days and 1 km for temporal and spatial resolution, respectively. The negative data was excluded before mapping the NDVI because these data usually represent areas covered by water or ice, rather than vegetation. Areas associated with value zero indicate no vegetation cover and areas associated with the value one indicates 100% vegetation coverage. When the NDVI value was lower than 0.05, the area could be regarded as bare land.

The eco-geographical regions were reclassified into humid area, humid/sub humid area, semi-humid area, semi-arid area and arid area according to the ratio of multi-year average potential evaporation to multi-year average precipitation (the aridity index) (Fu et al., 2001; Wu et al., 2002). The partition standards are shown in Table 1.

Elevation, slope gradient and aspect were obtained from the DEM data (the spatial resolution was 1 km). Land use types, which were obtained from the land use/land cover changes (LULC) database (1 km × 1 km), were divided into farmland, woodland, grassland, water area, residential land and unused land according to the National Standard of Land Use Status Classification of China. All the NDVI, DEM,

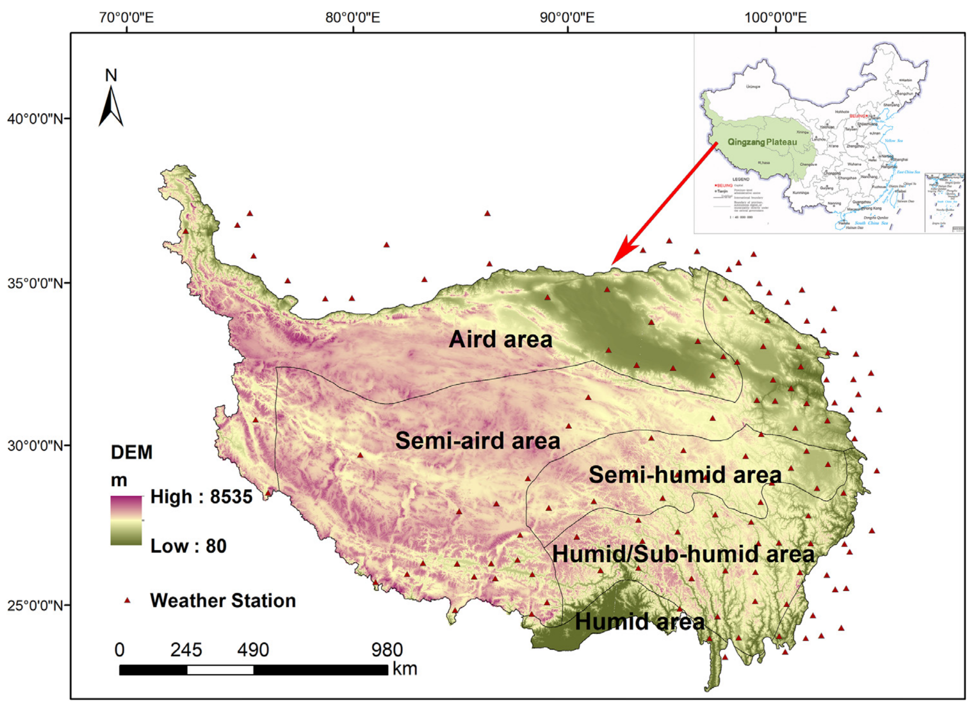

Fig. 1. The eco-geographical regions of the Qingzang Plateau, in China.

Table 1
Wet-dry condition division Index.

	Aridity Index	Natural Vegetation	Notes
Wet	≤0.49	Tropical rainforest	
Humid	0.50–0.99	Other forests	
Humid/sub humid	1.00–1.49	Forest steppe -(meadow)	Some of them have secondary salinization
Semi-humid	1.50–5.00 (on the Qingzang Plateau)	Steppe and meadow steppe Desert steppe	Can be dryland farming
Semi-arid	≥5.00 (on the Qingzang Plateau)	Desert	Need to irrigation
Arid	≥20.0	Desert	Need to irrigation

Data from: Resource and Environment Science and Data Center, China Academy of Sciences, http://resdc.cn/data.aspx?DATAID=125.

LULC and eco-geographical regions data were collected from the resource and environment data cloud platform of the Institute of Geographic Science and Natural Resources Research, Chinese Academy of Sciences (http://www.resdc.cn).

The annual precipitation and temperature data with 1 km × 1 km resolution were based on the climate data from the Data Center of China Meteorological Administration. A total of 132 weather stations were selected to obtain the daily temperature and precipitation data inside the Qingzang Plateau and its surroundings (Fig. 1). After excluding the data outliers (e.g., missing data or null value data), elevation was introduced as a covariable to perform the interpolation with ANUSPLIN (Hutchinson and Xu, 2013).

2.3. Statistical analysis

2.3.1. Spatial stratified heterogeneity and the controlling factors

The spatial differentiation and factor detection function of the geodetector model was used to identify the factors influencing the distribution pattern of annual NDVI on the Qingzang Plateau and analyze their contributions. The contribution rate of each factor to annual NDVI was calculated using equation (1) (Wang et al., 2016).

$$q = 1 - \frac{\sum_{h=1}^{L} N_h \sigma_h^2}{N\sigma^2} = 1 - \frac{SSW}{SST} \tag{1}$$

where $h = 1, \ldots, L$ represents the strata of the variable Y or the factor X; N_h represents the units amount in h layer; N represents the units amount in the total region; σ_h^2 represents the variable Y of the h layer; σ^2 represents the variable Y of the total region; SSW represents the within sum of squares; SST represents the total sum of squares. The range of q value was [0, 1] and the contribution of controlling factor X to landscape Y increased with a larger q value.

Interaction probes were used to identify interactions between natural factors. This is used to evaluate the interaction of the independent variables (natural factors) on NDVI. The first step is to calculate the q values of the two factors to annual NDVI, and the second step is to calculate the q value of the interaction of the two factors.

Topography (i.e., slope aspect, slope gradient, and elevation), meteorology (precipitation and temperature) and land use types were selected as X factors and the details are shown in Table 2. Land use and soil types were assigned according to the national standards of China.

2.3.2. NDVI, precipitation and temperature variations

Trend analysis was used to analyze the variations of annual NDVI, precipitation and temperature on the Qingzang Plateau from 1998 to 2018. This method was also used to conduct the pixel-by-pixel regression analysis of annual NDVI to analyze the trend of vegetation coverage change over time for each pixel. The regression slope, which represents the time variation characteristics of variables, was calculated using equation (2) (Wasserman, 2004).

$$\theta_{slope} = \frac{n\sum_{i=1}^{n} i \times fc_1 - \left(\sum_{i=1}^{n} i\right)\left(\sum_{i=1}^{n} fc_1\right)}{n \times \sum_{i=1}^{n} i^2 - \left(\sum_{i=1}^{n} i\right)^2} \tag{2}$$

Table 2
Details about the *X* factors.

Type	Factors	Index	Unit	Type	Factors	Index	Unit
Topography	X_1	Slope aspect	°	Meteorology	X_5	Temperature	°C
	X_2	Slope gradient	°		X_6	Precipitation	mm
	X_3	Elevation	m	Land use	X_7	Land use type	–
Soil	X_4	Soil classification	–				

Table 3
Trends of annual average temperature and precipitation from 1998 to 2018, in different eco-geographical regions.

	Qingzang Plateau	Humid	Humid/sub humid	Semi-humid	Semi-arid	Arid
Tem.	0.070	−0.524*	−0.030	0.652**	0.644**	0.428
Pre.	−0.011	−0.109	−0.355	0.064	−0.128	0.196

* Significant correlation at the 0.05 level (2-tailed)
** Significant correlation at the 0.01 level (2-tailed)

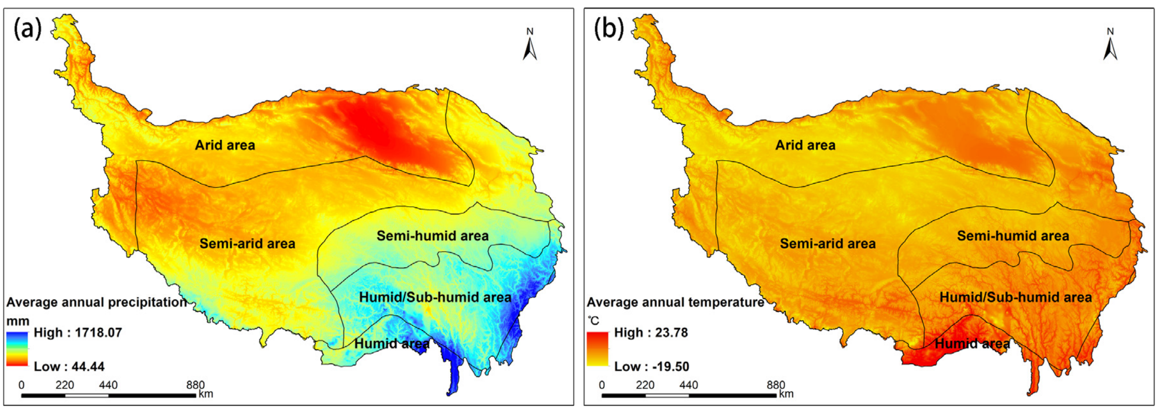

Fig. 2. Annual average (a) precipitation and (b) temperature.

where n represents the length of time, i represents the year and θ_{slope} represents the regression slope.

2.3.3. The relationship between vegetation coverage and explaining variables

The correlation between vegetation coverage and explaining variables was calculated by pixel-by-pixel correlation analysis. The correlation coefficient was calculated using equation (3) (Wasserman, 2004).

$$r_{xy} = \frac{\sum_{i=1}^{n} \left[\left(x_i - \bar{X}\right)\left(y_i - \bar{Y}\right) \right]}{\sqrt{\sum_{i=1}^{n} \left[\left(x_i - \bar{X}\right)^2 \sum_{i=1}^{n} \left(y_i - \bar{Y}\right)^2 \right]}} \quad (3)$$

where n represents the number of samples, $\bar{X}$ represents the mean value of the independent variable X, $\bar{Y}$ represents the mean value of the NDVI, and r_{xy} represents the correlation coefficient between the variables x and y.

3. Results

3.1. Precipitation, temperature and land use type variations from 1998 to 2018

The spatial distributions of annual average precipitation and temperature are shown in Fig. 2. The annual average temperature ranged from −19.5°C to 23.78°C and it was much colder in the north, a region with high altitude. The annual average precipitation varies from 44 mm in the northwest to 1718 mm in the southeast regions (Fig. 2).

The temporal variations of annual average precipitation and temperature are different at diverse eco-geographical regions (Fig. 3; Table 3). They varied between 295.49 mm to 566.22 mm, and −0.58 °C to 0.83 °C, between 1998 and 2018, respectively. For precipitation, there were no significant temporal variations for all the eco-geographical regions. The humid area had the lowest precipitation value in 2009, while other eco-geographical regions had the lowest value in 2015 (Fig. 3). For temperature, the values in humid/sub humid area decreased over the study period, and increased in the arid area, although no significant variation was recorded for these areas. The temperature of the humid region decreased ($p < 0.05$) and the values of semi-humid and semi-arid area increased ($p < 0.01$) significantly (Table 3).

The land use changes also showed strong spatial heterogeneity. The conversion from forestland and grassland to farmland and construction land accounts for 0.67% of the total area of the Qingzang Plateau, and the conversion from construction land and farmland to forestland and grassland accounts for 0.53%. These changes are mainly concentrated in the east and south parts. There was no significant land use change in 60.83% of the regions, mainly in the central part (Fig. 4).

3.2. Temporal and spatial variations of the vegetation distribution in different eco-geographical regions

The distribution of annual NDVI is shown in Fig. 5. The average annual NDVI decreased from the southeast to the northwest, and varied among different eco-geographical regions. The average annual NDVI values in humid area, humid/sub humid area and semi-humid (> 0.61) were much higher than those of the other areas. The average annual NDVI values of the arid area (0.12) were the lowest in Qingzang Plateau.

The change rates of annual NDVI at different eco-geographical areas from 1998 to 2018 are shown in Fig. 6. The annual NDVI values of humid area, humid/sub humid area, semi-humid area and semi-arid

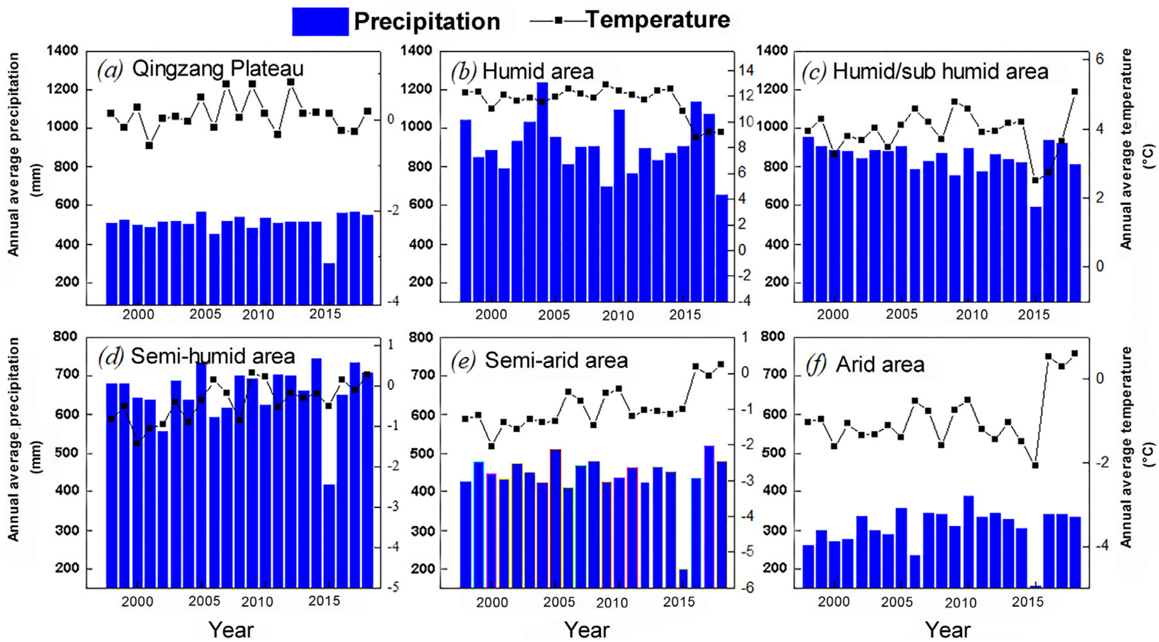

Fig. 3. Variations of precipitation and temperature in different eco-geographical regions from 1998-2018. Notes: (a) to (f) show the values in Qingzang Plateau, the humid area, the humid/sub humid area, the semi-humid area, the semi-arid area and the arid area, respectively.

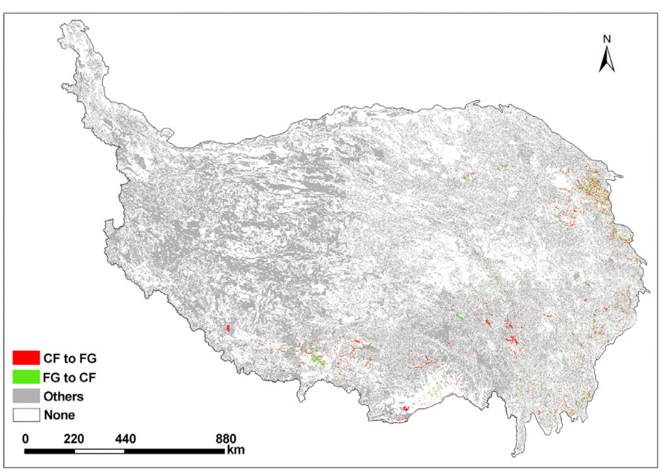

Fig. 4. Land use changes from 1998 to 2018. Notes: FG to CF represents the conversion of forestland and grassland to farmland; CF to FG represents the conversion of construction land and farmland to forestland and grassland; Others represents other kinds of land use conversions.

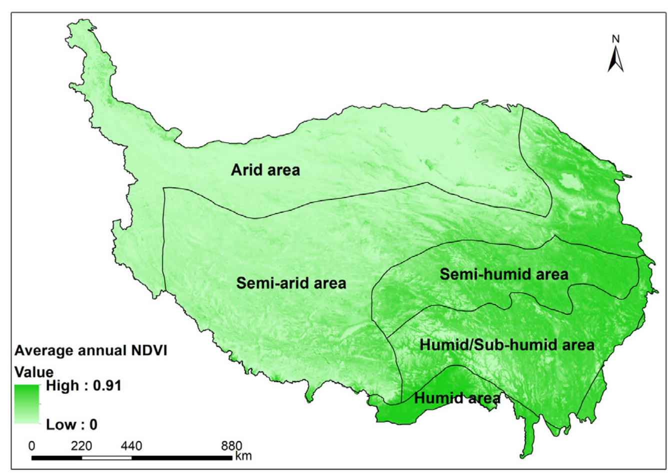

Fig. 5. Spatial distribution of annual NDVI.

area showed a significant increasing trend, but there was no significant change in the arid area. The overall average of annual NDVI increased 0.02 per year (Fig. 6). 47% of the vegetated area which was located mainly in the southwest part increased significantly (p < 0.05), while about 26% of the vegetated area located mainly in arid area decreased significantly (p < 0.05) (Fig. 7).

3.3. Factors influencing the temporal and spatial variations of annual NDVI

For the spatial distribution, contributions (q) of controlling factors to the annual NDVI are shown in Table 4. According to the geo-detector results, the top four controlling factors of the annual NDVI distribution were soil, precipitation, land use types and temperature, and the q values were 0.73, 0.55, 0.41 and 0.23, respectively. The main controlling factors are different in different eco-geographical regions (Table 4).

For the temporal distribution, the correlation coefficients between the annual NDVI and the annual accumulative precipitation as well as between the annual NDVI and the annual average temperature are shown in Table 5 and Fig. 8. NDVI and temperature showed significant negative correlations in semi-humid and semi-arid areas. Annual NDVI and precipitation showed significant positive correlation (p < 0.05) only in the arid area. 9.99% of the total area had significantly negative correlation (p < 0.05) between annual NDVI and temperature, and most of them were in the southeast. 13.12% of the area had positive correlation (p < 0.05) between annual NDVI and temperature, which were located mainly in the central part (semi-humid area and semi-arid area). 9.56% of the area had a significantly positive correlation (p < 0.05) between annual NDVI and precipitation. About 5.90% of the area had significantly negative correlation between annual NDVI and precipitation, and most of them were in the southeastern mountains.

The interacting impacts of variable pairs are shown in Table 6. All the factors enhance the contribution of each other to annual NDVI. Among them, interactions between aspect and elevation, aspect and tempera-

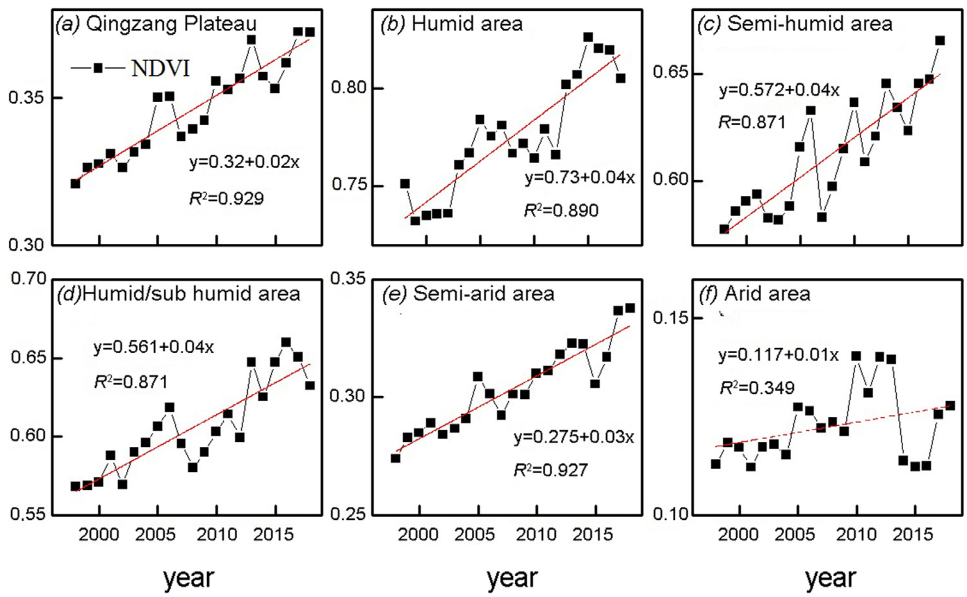

Fig. 6. Temporal variation of annual NDVI at different eco-geographical regions.

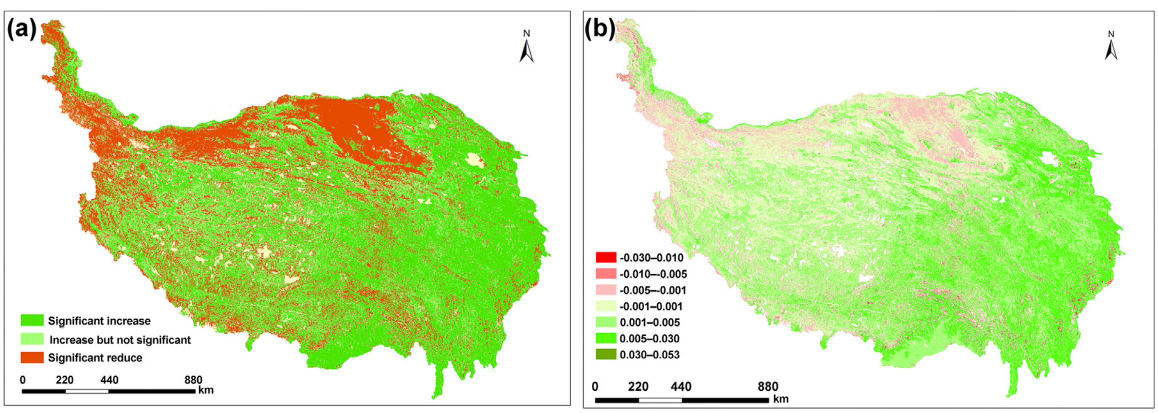

Fig. 7. The change trend (a) and rate (b) of annual NDVI from 1998 to 2018. Notes: Correlation is significant at the 0.05 level (2-tailed) in (a).

Table 4
The contributions (q) of controlling factors to annual NDVI in different areas of Qingzang Plateau of China.

	Aspect	Slope	Elev.	Tem.	Pre.	LULC	Soil
Qingzang Plateau							
q statistic	0.01	0.12	0.21	0.23	0.55	0.41	0.73
p value	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Arid area							
q statistic	0.01	0.03	0.05	0.03	0.05	0.14	0.208
p value	0.003	0.000	0.000	0.000	0.000	0.000	0.000
Semi-arid area							
q statistic	0.00	0.03	0.40	0.16	0.23	0.26	0.214
p value	0.124	0.000	0.000	0.000	0.000	0.000	0.000
Semi- humid area							
q statistic	0.02	0.01	0.63	0.51	0.10	0.23	0.369
p value	0.000	0.964	0.000	0.000	0.000	0.000	0.000
Humid/sub humid area							
q statistic	0.01	0.02	0.47	0.29	0.01	0.31	0.314
p value	0.000	0.019	0.000	0.000	0.000	0.000	0.000
Humid area							
q statistic	0.01	0.00	0.70	0.55	0.21	0.36	0.638
p value	0.003	1	0.000	0.000	0.000	0.000	0.000

Notes: LULC represents land use types; Elev. represents elevation; Tem. represents Temperature, and Pre. represents precipitation.

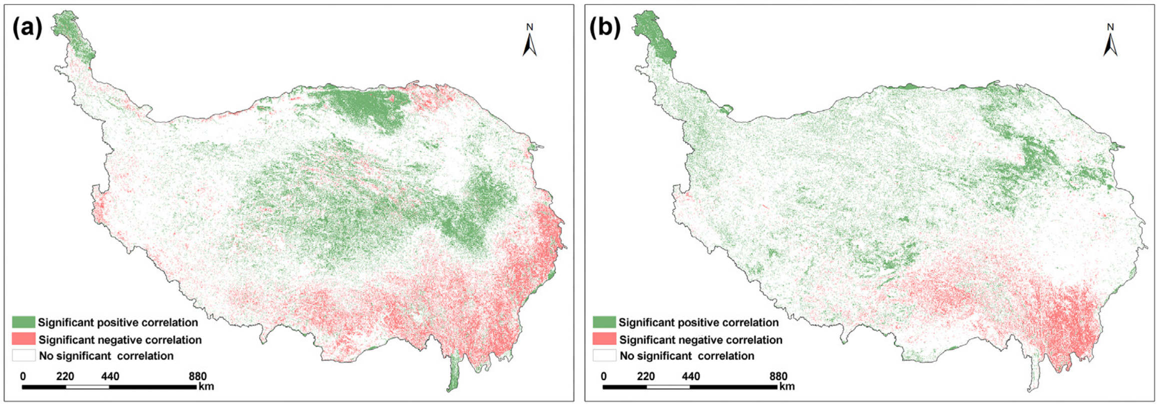

Fig. 8. Spatial variation in correlations between average annual NDVI and temperature (a) and precipitation (b). Notes: Correlation is significant at the 0.05 level (2-tailed).

Table 5
Correlations between annual NDVI and temperature, and precipitation, at different eco-geographical regions.

Correlation	Total	Humid	Humid/sub humid	Semi-humid	Semi-arid	Arid
Precipitation	0.127	0.055	−0.291	0.138	0.141	0.550**
Temperature	0.010	−0.513	−0.291	0.709**	0.657**	0.137

** Significant correlation at the 0.01 level (2-tailed)*Significant correlation at the 0.05 level (2-tailed)

Table 6
The interacting impacts of the variables to annual NDVI.

Interact factors	A	B	A + B	Interact result
Aspect ∩ LULC	0.008	0.406	0.410	Enhance, mutual
Aspect ∩ Slope	0.008	0.107	0.113	Enhance, mutual
Aspect ∩ Elev.	0.008	0.211	0.243	Enhance, nonlinear
Aspect ∩ Tem.	0.008	0.228	0.252	Enhance, nonlinear
Aspect ∩ Pre.	0.008	0.547	0.549	Enhance, mutual
Aspect ∩ Soil	0.008	0.733	0.737	Enhance, mutual
LULC ∩ Slope	0.406	0.107	0.428	Enhance, mutual
LULC ∩ Elev.	0.406	0.211	0.540	Enhance, mutual
LULC ∩ Tem.	0.406	0.228	0.507	Enhance, mutual
LULC ∩ Pre.	0.406	0.547	0.672	Enhance, mutual
LULC ∩ Soil	0.406	0.733	0.772	Enhance, mutual
Slope ∩ Elev.	0.107	0.211	0.330	Enhance, nonlinear
Slope ∩ Tem.	0.107	0.228	0.328	Enhance, mutual
Slope ∩ Pre.	0.107	0.547	0.553	Enhance, mutual
Slope ∩ Soil	0.107	0.733	0.739	Enhance, mutual
Elev. ∩ Tem.	0.211	0.228	0.323	Enhance, mutual
Elev. ∩ Pre.	0.211	0.547	0.744	Enhance, mutual
Elev. ∩ Soil	0.211	0.733	0.777	Enhance, mutual
Tem. ∩ Pre.	0.228	0.547	0.661	Enhance, mutual
Tem. ∩ Soil	0.228	0.733	0.754	Enhance, mutual
Pre. ∩ Soil	0.547	0.733	0.790	Enhance, mutual

Notes: LULC represents land use types; Elev. represents elevation; Tem. represents Temperature and Pre. represents precipitation. Notes: A and B represents the impact value of the single factor before and after "∩", and A+B represents the interactions of the two factors.

ture as well as slope and elevation displayed nonlinear enhancement, which was stronger than other interactions with mutual enhancement.

Based on the correlation values and the interacting results of variables, temperature and precipitation showed mutual enhancement, and the top four controlling factors had spatial heterogeneity (Table 7). The influence of precipitation was stronger than temperature in semi-arid and arid areas.

Table 7
The top four controlling factors for vegetation coverage in different eco-geographical regions.

Eco-geographical region	Top four controlling factors to vegetation coverage
Total	Soil, precipitation, land use type and temperature
Humid	Elevation, soil, temperature and land use types
Humid/sub humid	Elevation, soil, temperature and land use types
Semi-humid	Elevation, temperature, soil and land use types
Semi-arid	Elevation, land use type and precipitation, soil
Arid	Soil, land use types, elevation and precipitation

4. Discussion

4.1. Changing characteristics of vegetation distribution

NDVI has increased significantly in the past several decades in China, while the vegetation coverage decreased in some parts (especially the central part) of the Qingzang Plateau from 1982–1999 (Xu et al., 2018). Our study showed that NDVI from the humid area to semi-arid area increased significantly from 1998–2018. The area with vegetation increase was obviously larger than that of decrease (Fig. 6). Previous studies also indicated that the vegetation expansion in most part of this region is at a nonlinear rate (Zhao et al., 2013; Anderson et al., 2020; Sigdel et al., 2020). While for the spatial distribution characteristics, the variation rate decreased from humid area to semi-arid area, with no significant increase in the arid area (Fig. 6). As the value of vegetation coverage also decreased from humid to arid regions (Fig. 6), this variation increased the spatial heterogeneity of vegetation coverage, and the vegetation in arid areas is under serious threat.

Although the increased vegetation coverage improves surface protection and the amount of carbon dioxide removed from the atmosphere, the vegetation in the Qingzang Plateau face many potential threats (Zhao et al., 2017). The first one was vegetation degradation (Feng et al., 2005; Cai et al., 2014). Previous studies showed that 52.44% of the total forest area and 41.8% of the total grassland area degraded from 2010–2015 and only farmland and sparse vegetation remained stable in the Qingzang Plateau (Wang et al., 2019a). Based on our results, land use type was an important controlling factor of vegetation distribution (Table 7), and changed dramatically in the east and south parts of the Qingzang Plateau (Fig. 4). NDVI increased in these areas (Fig. 6). That might be because not all degradation would result in the decrease of vegetation coverage, but because of the negative influence on community structure or plant functional traits (Bao et al., 2015; Zhang et al., 2017). Taking grass degradation as an example, shrub encroachment has reduced the coverage of grassland to shrub belts and shrub dunes, which could make the surface area covered by grass to decrease, enlarging the space between shrubs (Eldridge et al., 2015; Hu et al., 2015). Shrubs also increased the spatial heterogeneity of soil nutrients and decrease the food of wild animals and livestock. In the long run, shrub encroachment would further aggravate soil loss and worsen local environment (Zhou et al., 2006; Tian et al., 2019). In addition, the heavy trampling caused by high intensity grazing would limit the grassland (Xiao et al., 2018). The second threat was the unreasonable introduction of plantation. The species structure of restored forest was often simple and the resilience was low (Li et al., 2017; Li et al., 2018b). Studies in the adjacent plateau were shown that high density planting or inappropriate species selection would lead to excessive use of groundwater and deep soil water (Fang et al., 2016; Feng et al., 2016). All these changes would seriously threaten the sustainability of vegetation on the Qingzang Plateau. Although vegetation coverage in this Qingzang Plateau was increasing, changes in ecosystem functions and services required further study.

4.2. The influence of environmental factors on vegetation distribution

Many studies have indicated that climate change has resulted in the changes of characteristics and functional traits of vegetation communities in both Qingzang Plateau and its surroundings. A previous study showed that the correlation between NDVI and precipitation was negative between 1989 and 1999 on the Qingzang Plateau because of the shorter growing season resulting from snow and ice cover increase (Piao, 2003). While from 1998 to 2018, the correlations between NDVI and precipitation were positive from semi-humid to arid areas and negative for humid/sub humid and humid areas (Table 5). This may be because the increasing temperature expands the space for vegetation growth and precipitation becomes the main limiting factor from semi-humid to arid areas. The frequency of extreme events might increase, according to the Fifth Assessment Report of the IPCC (Stocker et al., 2013a). The most recent was an extreme drought affecting several parts of China in 2015. Studies on the adjacent plateau showed that some seeds or plants died, and the characteristics of plants that survived changed dramatically in that year (Zhang et al., 2019). Correspondingly, the vegetation coverage was also the lowest in recent years on the Qingzang Plateau (Fig. 6).

The impacts of extreme drought varied among different eco-geographical regions and NDVI in semi-humid and semi-arid areas decreased most significantly in 2015 (Fig. 6). According to our study, the most significant temperature increases also occurred in the semi-arid and semi-humid areas (Table 3). For most parts of these regions, this extreme drought occurred with low temperature (Fig. 3). It may be because the southwest monsoon did not bring enough warm and humid air, or lower temperature decelerated the melting of glaciers, which in turn reduced the source of water in the air which forms precipitation. Existing studies had shown the interactive impacts of temperature and precipitation on vegetation coverage. The temperature and precipitation interaction affected the climbing rate of tree lines through influencing the plant interspecific relationship, so that it would present a non-linear rising trend (Wang et al., 2019b; Anderson et al., 2020; Sigdel et al., 2020).

Other variables also showed interactive impacts on vegetation coverage. Soil was the growth matrix of plants, and had great influence on the spatial distribution of vegetation, especially in the arid area. Soil properties changed under the influence of land cover change, and vegetation further modified soil properties. Within a limited region, the spatial heterogeneity and temporal heterogeneity of soil types were relatively small, and the distribution pattern of soil types changed little in the short term, which might be the reason why soil types and other factors did not show nonlinear enhancement (Table 6). As the temperature decreased with elevation, the three groups of nonlinear enhancement interactions could be regarded as the enhancement among elevation, aspect and slope (Table 6). Previous ecological restoration projects usually set a constant slope. For example, for the *Grain for Green* project in China, all farmlands with slope above 25 degrees are required to be converted into forest or grassland (Wang et al., 2004; Lv et al., 2012). This kind of setting might not be suitable on the Qingzang Plateau because the same slope might have completely different characteristics at different elevation (Table 6). In addition, elevation was the top factor that influenced the vegetation coverage from humid to semi-arid areas. Therefore, the spatial heterogeneity of elevation should consider for large-scale ecological restoration schemes in this area.

4.3. Implications for ecological restoration

In the recent 20 years, human activities have influenced the vegetation distribution on the Qingzang Plateau, especially in the eastern and southern areas where cities and towns are concentrated (Fig. 4). In these areas, the construction of railways and roads cut off the natural corridors and the urban expansion destroyed large areas of vegetation (Zheng et al., 2007; Luo et al., 2020). A series of ecological protection and restoration projects have been launched on the Qingzang Plateau, for mitigation and adaptation of vegetation to the negative impacts of climate change and human activities (He et al., 2020; Liu, 2020; Tarolli and Straffelini, 2020; Wang and Zhong, 2019; Wang et al., 2019c). The ecological protection and restoration strategy as well as appropriate management could support the sustainable construction and protection of vegetation restoration in this region (Fu, 2020; Wang and Zhong, 2017). Although some of the projects only focused on the importance of project construction layout and neglect the evaluation of ecosystem resilience, there were increasing number of projects considering the nature-based solutions as the development of international ecological protection concept (Fig. 9). For example, the *Ecological Protection and Restoration Projects for Mountain - River - Forest - Field - Lake - Grassland,* which were launched in 2016, raised importance to the relationships and interactions between landscape elements in the regional complex ecosystem. Based on the results of this study and previous studies, suggestions were put forward for vegetation sustainability in this region.

Firstly, spatial heterogeneity and interaction of the main influencing factors on vegetation distribution should be considered when policymakers select the vegetation restoration strategies. Based on results from this study, the spatial heterogeneity of precipitation and temperature were low, and soil properties and land use changes were the main factors impacting the vegetation distribution in the arid area (Fig. 2; Table 7). Ecological restoration in this eco-geographical region should focus on protection and improvement of the construction of national parks and protected areas. Vegetation and temperature variations changed more frequently than that of other eco-geographical regions both of semi-arid and semi humid areas (Fig. 2, 5), and many river headwaters were located in this region. So, these eco-geographical regions could be regarded as the key zones of ecological restoration planning and adjusted measures to local conditions should be selected for different elevations. In the humid/sub humid and humid areas, moderate precipitation and temperature are conducive to plant growth, while their special glacial conditions and higher population density lead to higher vulnerability to vegetation restoration. Therefore, this eco-geographical region should be more sensitive to the risk of temperature rise. The ecological restoration in this area should identify areas with the most human disturbance, and set up buffer zones between areas of high intensity human activity and natural areas. Based on the buffer zones, a new pattern of harmonious coexistence between human and natural plants/animals needs to

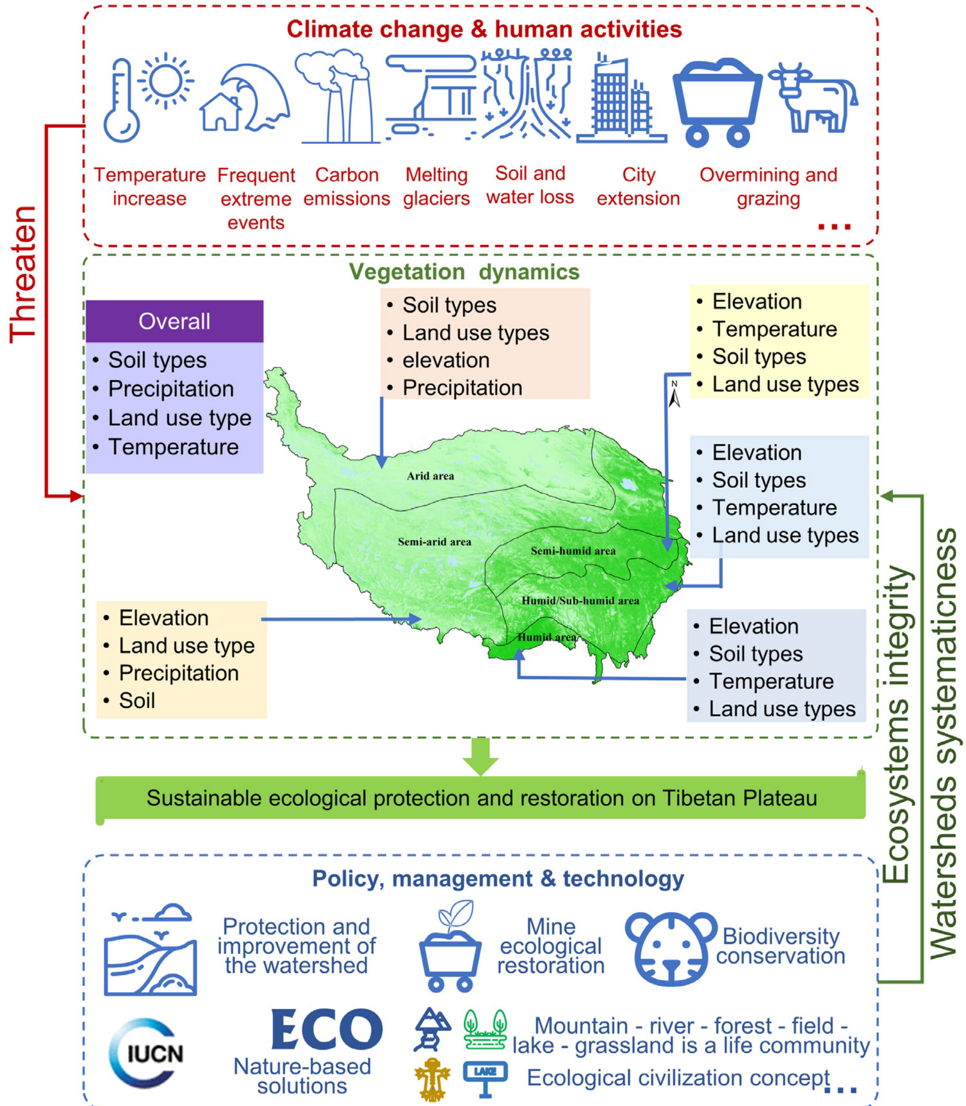

Fig. 9. Framework for controlling factors affecting vegetation dynamics and its implications for land management.

be found, since the percentage of land use conversion from forest or grassland to farm or construction land was high (Fig. 4). In addition, soil and water conservation facilities should also be increased in this area to reduce and prevent soil erosion caused by geological disasters.

Secondly, it was important to assess the changes of ecosystem service functions in addition to vegetation coverage. As showed before, both the coverage and the rate of increase were increasing over the study period, while the land use changes showed important impacts on vegetation (Fig. 4). So, only considering vegetation coverage might overlook the ecosystem health, and ecosystem service would be an indicator of the overall state of an ecosystem. Ecosystem services could also serve as a bridge to maintain positive interactions between mountain-river-forest-field-lake-grassland, human well beings and sustainable development (Wang and Zhong, 2019). In different eco-geographical regions, the vegetation dynamics and their relationships to controlling factors were different. Combining with some studies on ecosystem services, more attention on the water conservation services should be paid on the arid area, while in humid area considerations should focus on food supply and carbon sequestration services. In addition, it was necessary to maintain the tradeoff between ecosystem services through follow-up regulatory policies after the project implementation period.

Thirdly, the selection of an ecological restoration strategy should consider the temporal and spatial scales. The main impact factors of vegetation variation showed obvious spatial heterogeneity, and the differences were large across eco-geographical region scale and the whole region scale (Fig. 6; Table 4, 5, 6). In addition, Qingzang Plateau belonged to a larger geographical unit (Yao et al., 2017). The Qingzang Plateau served as the water source of rivers and a natural barrier because of its special geographical location and geomorphic type, and it showed impacts on the surrounding areas. Therefore, the integrity of the ecosystem and the systematics of the watershed should be considered in the establishment of the ecological restoration strategy to avoid the artificial separation of the natural links between ecological elements in the restoration. For temporal scales, short-term fluctuations of the factor may be contained in long-term dynamic regularity, and these changes were continuous. For example, the annual variation of NDVI fluctuated while the overall trend was increasing (Fig. 6). Then the process mechanism of ecosystem pressure-state-response and the overall ecosystem function should also be discussed to develop sustainable ecological restoration strategies in Qingzang Plateau.

Fourthly, to improve the synergy of ecological restoration project and avoid some potential risks, advanced experience of international concepts, management strategies, and technologies could be referenced in the specific planning and implementation process. For the arid area where the vegetation dynamics were sensitive to land use types (Table 7), the Natural-based Solution and Rewilding, proposed by the

IUCN and the Global Wilderness Foundation, could be referenced for the establishment and management of national parks and nature reserves (Lorimer et al., 2015; Pontee et al., 2016; Albert et al., 2017; Qu et al., 2020). For the semi-arid and semi humid areas where the response of NDVI to extreme drought was obvious (Fig. 3, 6), the long-term grazing exclusion using fences was bringing serious damage to wildlife and corridors. Now it is being dismantled in some places (Sun et al., 2020) and new management patterns or technologies could be explored such as the mob-grazing and the High-Tensile Electric Fence Designs to retain the good function of the fence without harming animals and the natural corridors (Karhu and Anderson, 2006; Leblond et al., 2007; Russell et al., 2013; Bartimus et al., 2016; Van Eden et al., 2016; Mesleard et al., 2017). For the humid/sub-humid and humid areas with land use conversion (Fig. 4), restoration strategies should be under the framework of coupled human and environment systems to realize the harmony between human and nature (Liu et al., 2007; Galvani et al., 2016; Zhao et al., 2018).

4.4. Limitations of this study

In this study, the impact factors on vegetation considered environmental factors such as soil, elevation, land use type, slope, aspect, precipitation and temperature. However, the human activities such as grazing, city expansion and mining also influence the vegetation dynamics inside and in the buffer zones of Qingzang Plateau. In addition, quantitative research on the feedbacks between soil properties and vegetation change is needed. Therefore, these impact factors need further studies and the current remote sensing-based results need validation using field observations in the future. Lastly, NDVI was used to indicate vegetation coverage in this study, which is reasonable in this mostly spare vegetated region, but we acknowledge that NDVI changes were not always associated with vegetation coverage and could be due to greener leaves or changes in community species composition.

5. Conclusions

This study analyzed the spatial and temporal variation of vegetation in different eco-geographical regions on the Qingzang Plateau from 1998 to 2018, and identified the main controlling factors of vegetation coverage variation and their interactions. The distribution pattern of vegetation was similar to that of precipitation and temperature on the Qingzang Plateau. For the whole region scale, NDVI decreased gradually from southeast to northwest. Vegetation in humid regions was significantly higher than that of other subregions, and NDVI in arid regions was the lowest. The controlling factors of vegetation distribution varied in different scales. Precipitation was the most important factor affecting vegetation distribution for the whole region, while in most sub-areas it was elevation. The interannual variation of NDVI was greatly influenced by temperature. In the context of global warming, the stability of vegetation restoration needed to be maintained.

Land use was an important factor affecting the distribution of vegetation on the Qingzang Plateau. The northwestern part of the Qingzang Plateau is suggested to be protected, while the southeastern part is suggested to build a harmonious human-nature coupling relationship. The changes of ecosystem services and their influencing factors, scale effects and interactions between controlling factors should be fully considered when designing ecological restoration strategies of different scales. The planning and construction of ecological conservation and restoration projects on the Qingzang Plateau required scientific and detailed demonstration as well as monitoring and evaluation, so that it could better play the role of "water tower of Asia" and ecological barrier.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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