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Trend analysis of vegetation dynamics in Qinghai–Tibet Plateau using Hurst Exponent

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ABSTRACT

As one of the most sensitive areas responding to global environmental change, especially global climate change, Qinghai–Tibet Plateau has been recognized as a hotspot for coupled studies on global terrestrial ecosystem change and global climate change. As an important component of terrestrial ecosystems, vegetation dynamic has become one of the key issues in global environmental change, and numerous case studies have been conducted on vegetation dynamic trend in different study periods. However, few are focused on the quantitative analysis of the consistency of vegetation dynamic trends after the study periods. In the study, taking Qinghai–Tibet Plateau as a case, vegetation dynamic trend during 1982–2003 were analyzed, with the application of the method of linear regression analysis. The results showed that, vegetation dynamics in Qinghai–Tibet Plateau experienced a significant increasing as a whole, with nearly 50% forest degradation in the study period. And among the 7 kinds of vegetation types, the change of forest was the most fluctuant with desert the least one. Furthermore, the consistency of vegetation dynamic trends after the study period, was quantified using Hurst Exponent and the method of R/S analysis. The results showed high consistency of future vegetation dynamic trends for the whole plateau, and inconsistent areas were mainly meadow and steppe distributed in the middle or east of the plateau. It was also convinced that, vegetation dynamic trends in the study area were significantly influenced by topography, especially the elevation.

1. Introduction

Vegetation is not only the main part of terrestrial ecosystems on earth (Piao and Fang, 2003; Godinez-Alvarez et al., 2009), but also the important medium for energy exchange, water cycle and biogeochemical cycle in terrestrial surface. Linking the material circulation and energy flow among pedosphere, hydrosphere and atmosphere, vegetation plays an irreplaceable role at the global scale in regulating carbon balance, reducing greenhouse gases and maintaining climate stability (Piao and Fang, 2003; Hu et al., 2010). Sensitive to climate change (Yang and Piao, 2006), vegetation dynamics have been recognized as one of the key issues in global change of terrestrial ecosystems (Rikie et al., 2007; Fu et al., 2007, 2010; Kelly et al., 2011).

Due to large area coverage and long time series span, remotely sensed data has become the most important data source for monitoring vegetation dynamics at large scales (Tucker et al., 2001; Ludwig et al., 2007; Zhao et al., 2009; Zhang et al., 2011). Widely used as the parameter of vegetation dynamics, vegetation index (VI) refers to the quantitative value measuring vegetation conditions and is often obtained through the combination of different spectral of remote sensing data. Because of its sensitivity to vegetation growth status, productivity and vegetation cover types (Tucker, 1979), normalized difference vegetation index (NDVI) has been the most widely used indicator to represent vegetation status among various vegetation indices. With high temporal resolution, National Oceanic and Atmospheric Administration Advanced Very High Resolution Radiometer (NOAA-AVHRR) data sets have become the most significant data source of terrestrial vegetation dynamic studies at large scales since 1980s, although their spatial resolution are a little coarse. Furthermore, as the correction of Pathfinder land (PAL) data sets (Tucker et al., 2001), Global Inventory Monitoring and Modeling Studies (GIMMS) NDVI data sets can eliminate the influence of volcanic eruptions, solar elevation angle and sensor sensitivity, and thus has been widely used in studies on global or regional vegetation dynamics (Tucker et al., 2001; Piao and Fang, 2003).

As a sensitive area to climate change with great ecological vulnerability, Qinghai–Tibet Plateau is a suitable place for the study on the response of terrestrial ecosystems to climate change (Yang and Piao, 2006). Various studies have been conducted on the trends of vegetation dynamics in Qinghai–Tibet Plateau using NDVI time series. Piao and Fang (2003) analyzed the inter-annual vegetation

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changes in China based on PAL data sets, and pointed out that vegetation change in Qinghai–Tibet Plateau was the most significant in all four seasons. Using GIMMS NDVI data sets, Fang et al. (2004) put forward that vegetation activity was increasing in most area of Qinghai–Tibet Plateau during 1982–1999. Based on the same data source, Yang and Piao (2006) found out that it was spring which experienced the largest growth rate of vegetation in four seasons, while Hua et al. (2008) analyzed the spatial differentiation of vegetation dynamic trend in Qinghai–Tibet Plateau during the same study period. Zhou et al. (2007) acquired the similar increasing trend on vegetation dynamics in Qinghai–Tibet Plateau, although there were some fluctuations in the process of vegetation change. However, few studies were focused on comparing the dynamic trends of different vegetation types.

As to the methodology for analyzing vegetation dynamic trends, the method of linear regression analysis was mostly used with remotely sensed time serial NDVI data. In the method, vegetation dynamic trends were analyzed through calculating the regression slope and correlation coefficient. Although the method was criticized to be unable to reflect non-linear characteristics in the process of vegetation dynamics (Li et al., 2008), and mutation would be smoothed in regression process, it was still widely used in large-scale vegetation dynamic studies, because of its simplicity and robustness (Rasmus et al., 2009).

As we knew, vegetation dynamic trends not only referred to the prevalent directions of vegetation dynamics in time series of the study period, but also indicated possible directions of vegetation dynamics after the study period. And the latter was more important under the background of global climate change (Li et al., 2008), since it could really respond to vegetation change in the future. However, compared with numerous case studies on vegetation dynamic trends in the past, few studies were focused on the trends in the future. This might be due to the non-linear characteristics of vegetation dynamics in long time series, which made it unable to simulate vegetation change in the future with simply linear regression analysis. Furthermore, because of uncertainties in future climate change and lag effects of vegetation change to climate change (Braswell et al., 1997; Piao and Fang, 2003; Fabricante et al., 2009), it was difficult to simulate future vegetation change through correlation models between vegetation activity and associated influencing factors.

Estimated through the method of R/S analysis, Hurst Exponent (H) was more and more used to quantitatively detect the consistency of long time series data in the nature. The exponent was originally proposed by Hurst (1951) to analyze the time series flow data of Nile River, with theoretical improving by Mandelbrot and Wallis (1969). At present, as a non-parametric analysis method, R/S analysis had been widely used in financial field due to its robustness (Sánche et al., 2008), while it had not been applied in the time series detection of vegetation dynamics.

Therefore, taking Qinghai–Tibet Plateau as a case study area, vegetation dynamic trend during 1982–2003 were analyzed using GIMMS–NDVI data with the application of linear regression analysis method and Hurst Exponent. More specifically, the aims of this study were to analyze vegetation dynamic trends of the plateau as a whole with trends comparison of various vegetation types, to characterize spatial differentiation of vegetation dynamics, and to detect the consistency of vegetation dynamics after the study period.

2. Materials and methods

2.1. Study area

Qinghai–Tibet Plateau lies in the southwest of China, covering the whole of Tibet and Qinghai provinces, and part of Xinjiang, Gansu, Sichuan, and Yunnan provinces (Fig. 1). With the average elevation of over 4000 m, Qinghai–Tibet Plateau is known as roof of the world. Because of its unique topography and geographical location, Qinghai–Tibet Plateau forms the azonal climate, which brings about a great impact on global climate change and results in the formation of Asian monsoon climate (Mo et al., 2004). Combined with the factors such as elevation, latitude and distance from the sea, the plateau climate in the study area shows a gradient from warm and humid in southeast to cold and dry in northwest, which leads to spatial differentiation of vegetation types. It appears in turn from forest to meadow, steppe and desert in vertical direction. Especially in the south of the Himalayas, vegetation cover changes upward from tropical rain forest to broad leaf forest, needle leaf forest, shrub, meadow and snow zone, which makes up a complete vertical spectrum of mountain vegetations (Yu and Xu, 2009).

2.2. Data source

Three types of datasets were used in this case study, i.e. NDVI data, vegetation data and elevation data. All the datasets were unified according to the following parameters: (1) Central Meridian, 105°; (2) Latitude of Origin, 0°; (3) Standard Parallel 1, 25°; (4) Standard Parallel 2, 47°; (5) Projection, Albers Equal Area Conic; and (6) Datum, Krasovsky.

2.2.1. NDVI data

AVHRR GIMMS NDVI dataset was used in the study and acquired from the UMD-GLCF (University of Maryland, Global Land Cover Facility) data center. The spatial resolution is 8 km × 8 km, and the temporal resolution is 16 days. The method of common maximum value composite (MVC) was used to compile monthly NDVI dataset, as it could minimize atmospheric effects, scan angle effects, cloud contamination and solar zenith angle effects (Holben, 1986). Moreover, in order to avoid the influence of negative value of water body, pixels values below zero were reassigned to be zero. Through the monthly GIMMS NDVI dataset, annual mean NDVI for each year and mean annual NDVI during 1982–2003 in the study area were calculated and mapped (Fig. 2).

2.2.2. Vegetation data

The digitized vegetation map (1: 4,000,000) was acquired from Environmental and Ecological Science Data Center for West China, National Natural Science Foundation of China. In the vector map, vegetation types in Qinghai–Tibet Plateau were classified as follows: needle leaf forest (5.9%, area ratio, the same as below), broad leaf forest (2.5%), shrub (19.8%), desert (19.6%), steppe (22.5%), meadow (18.4%), and crop (1.1%); while non-vegetation area (8.9%, including sand dune, gobi, bare rock and glacier) and water body (1.3%, mainly plateau lakes), were also mapped (Fig. 3). In sum, 89.8% of the study area was covered with natural or agricultural vegetations.

2.2.3. Elevation data

The elevation data set was also acquired from Environmental and Ecological Science Data Center for West China, National Natural Science Foundation of China. The spatial resolution of elevation data was 1 km × 1 km, and was reset to be 8 km × 8 km using cubic convolution resample method (Fig. 4).

2.3. Linear regression analysis

The method of linear regression analysis was widely used in vegetation dynamics detection with time series NDVI data. In the method, time t was set as the independent variable with NDVI value of each pixel for dependent variable, and the slope of linear regression was the very index quantifying the trend of vegetation

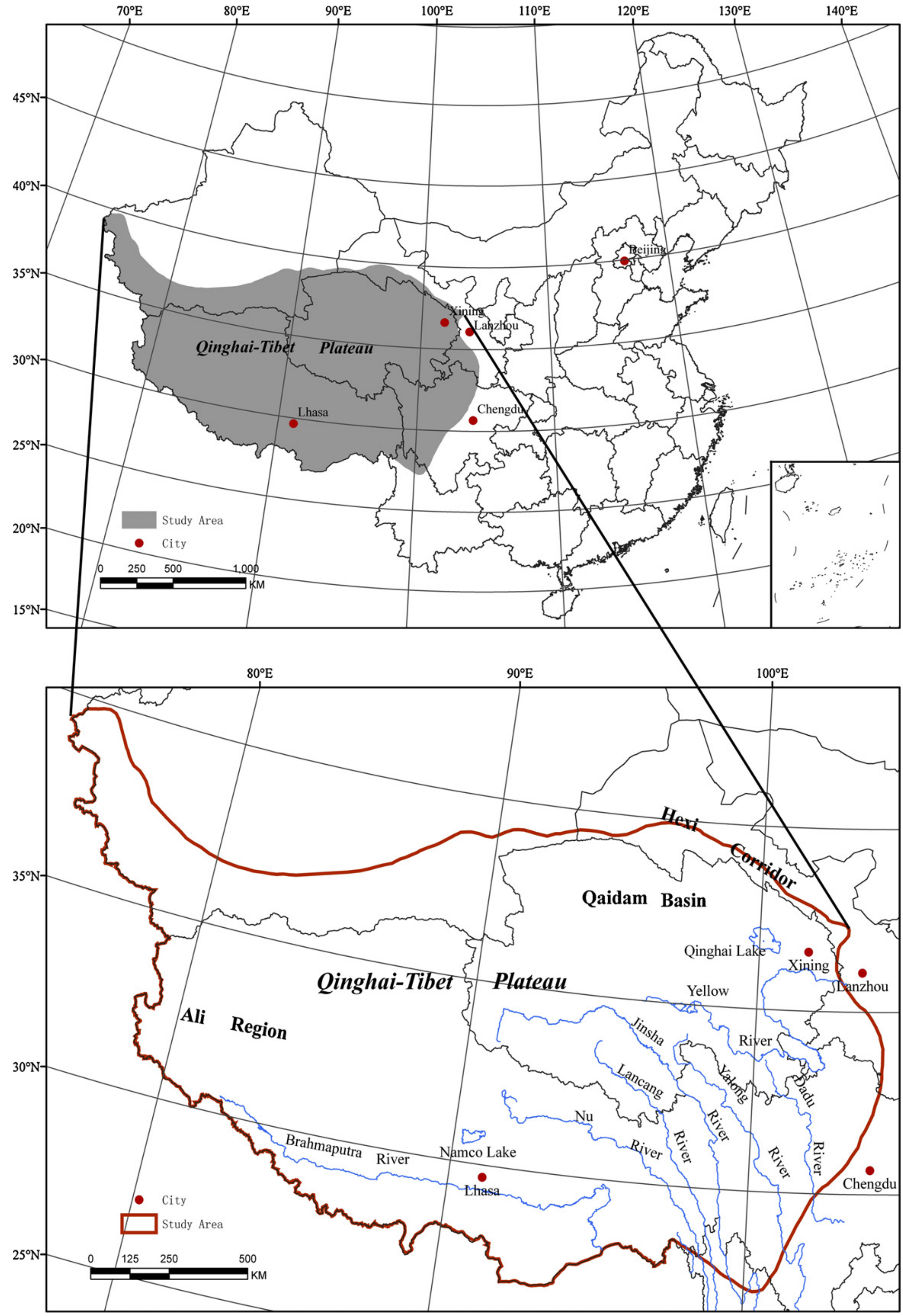

Fig. 1. Location of the study area.

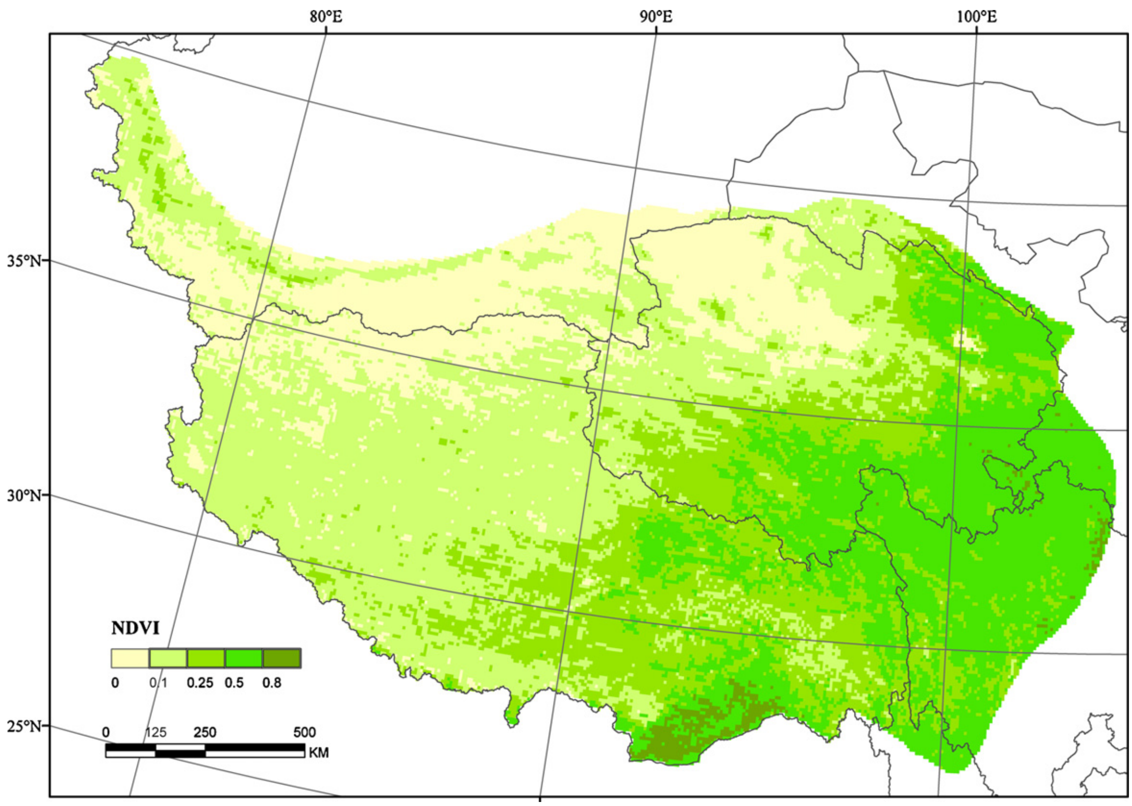

Fig. 2. Mean annual NDVI in Qinghai–Tibet Plateau during 1982–2003.

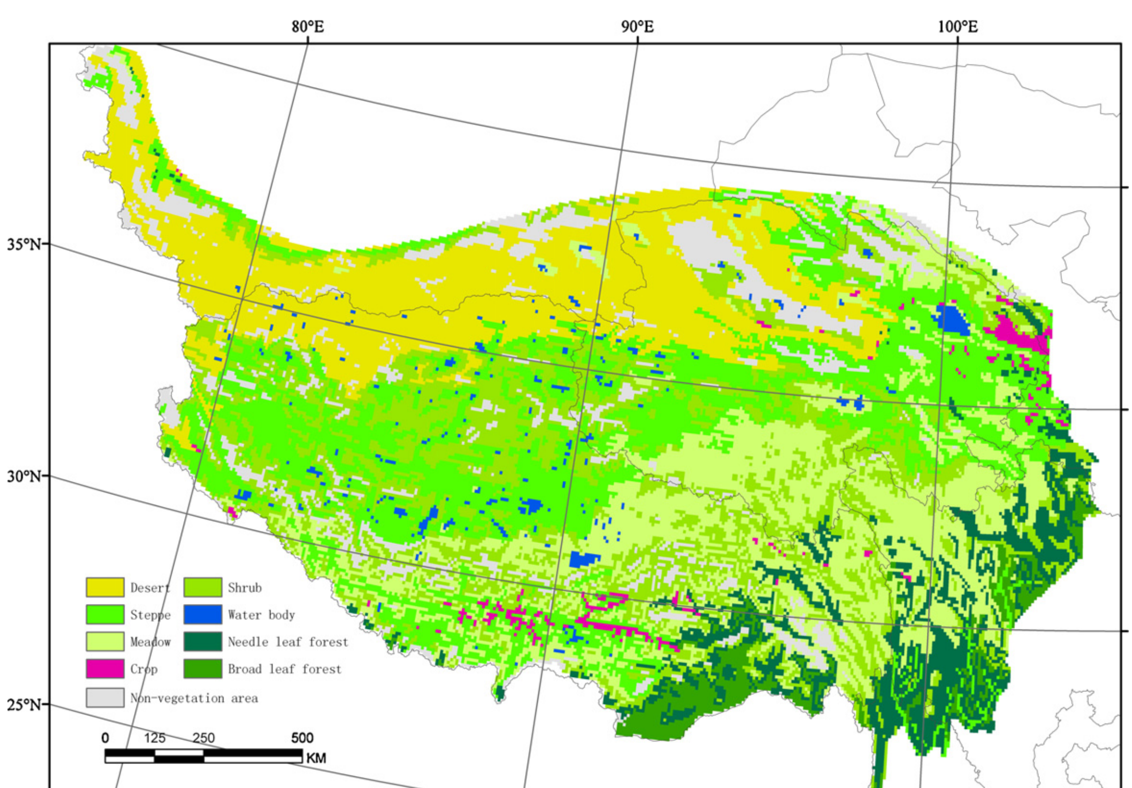

Fig. 3. Spatial distribution of vegetation types in Qinghai–Tibet Plateau.

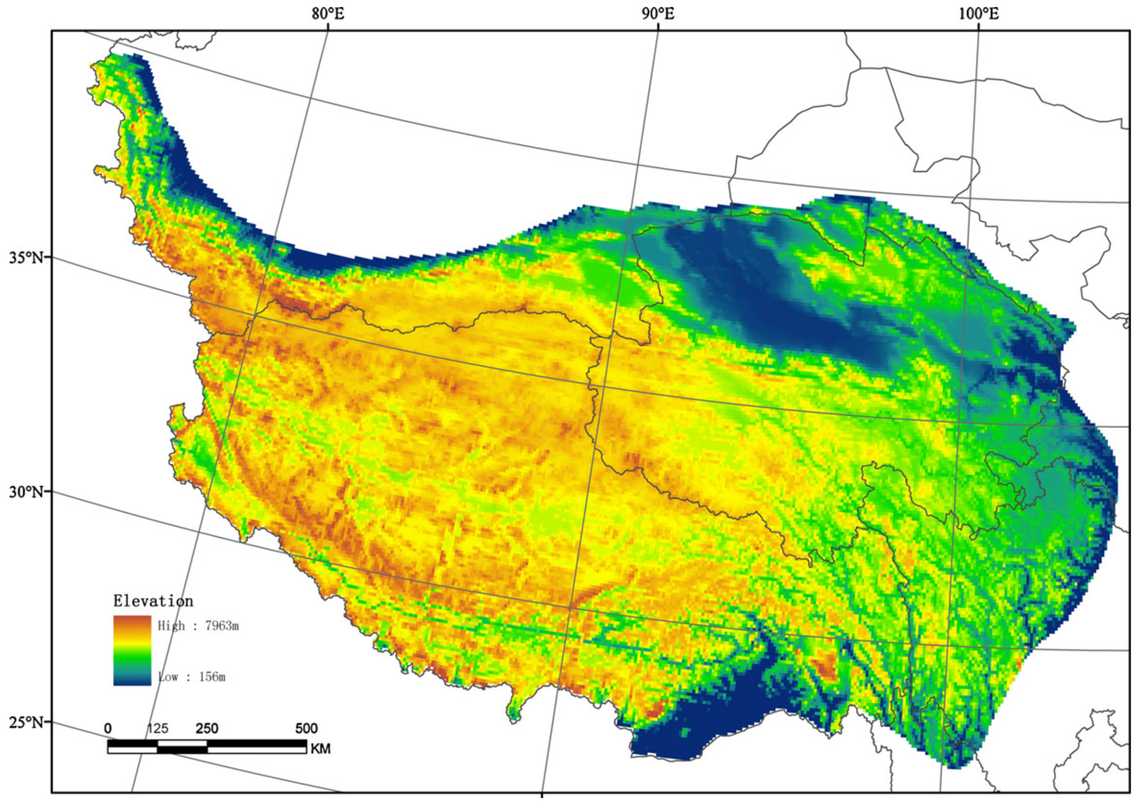

Fig. 4. Elevation in Qinghai–Tibet Plateau.

dynamics in the study period. In details, plus value of the slope referred to positive trend of vegetation dynamics, which meant increasing of vegetation coverage or enhancing of vegetation activity; and minus value of the slope referred to negative trend of vegetation dynamics, which meant decreasing of vegetation coverage or weakening of vegetation activity. The calculation of the slope was as follows:

$$\text{Slope} = \frac{n * \sum_{i=1}^{n} i * \text{NDVI}_i - (\sum_{i=1}^{n} i)(\sum_{i=1}^{n} \text{NDVI}_i)}{n * \sum_{i=1}^{n} i^2 - (\sum_{i=1}^{n} i)^2} \quad (1)$$

where n is the number of years in the study period, i is the serial number of the year, and NDVI_i is NDVI value in the year i.

Significance test of vegetation dynamic trend was conducted using the correlation coefficient of the linear regression. The calculation of the correlation coefficient was as follows:

$$r = \frac{cov(i, \text{NDVI}_i)}{\sqrt{\text{Var}(i)\text{Var}(\text{NDVI}_i)}} \quad (2)$$

where i is the serial number of the year in the study period, NDVI_i is NDVI value in the year i, cov referred to covariance function, and Var referred to variance function.

2.4. Hurst Exponent and R/S analysis

R/S analysis was the eldest and best-known method to estimate Hurst Exponent. The main calculation procedures were as follows (Sánche et al., 2008):

1. To divide the time series $\{\xi(\tau)\}$ ($\tau = 1, 2, \ldots, n$) into τ sub series $x(t)$, and for each sub series $t = 1, \ldots, \tau$.
2. To define the mean sequence of the time series,

$$\langle\xi\rangle_\tau = \frac{1}{\tau}\sum_{t=1}^{\tau} x(t), \quad \tau = 1, 2, \ldots, n \quad (3)$$

3. To calculate the cumulative deviation,

$$X(t, \tau) = \sum_{u=1}^{t} (\xi(u) - \langle\xi\rangle_\tau), \quad 1 \le t \le \tau \quad (4)$$

4. To create the range sequence,

$$R(\tau) = \max_{1 \le t \le \tau} X(t, \tau) - \min_{1 \le t \le \tau} X(t, \tau), \quad \tau = 1, 2, \ldots, n \quad (5)$$

5. To create the standard deviation sequence,

$$S(\tau) = \left(\frac{1}{\tau}\sum_{t=1}^{\tau} (\xi(t) - \langle\xi\rangle_\tau)^2\right)^{1/2}, \quad \tau = 1, 2, \ldots, n \quad (6)$$

6. To rescale the range,

$$\frac{R(\tau)}{S(\tau)} = (c\tau)^H \quad (7)$$

According to Hurst (1951) and Mandelbrot and Wallis (1969), the value of Hurst Exponent expanded from 0 to 1. When the value was equal to 0.5, it meant that the time series was a stochastic series without consistency, which indicated that change trend of the time series in the future would be irrelated with that in the study period; when the value was greater than 0.5, it referred to the consistency of the time series, which indicated the same change trend of the time series in the future, with the greater value for the more consistency; and when the value was less than 0.5, it referred to the anti-consistency of the time series, which indicated anti-trend of the time series in the future, with the less value for the more anti-consistency.

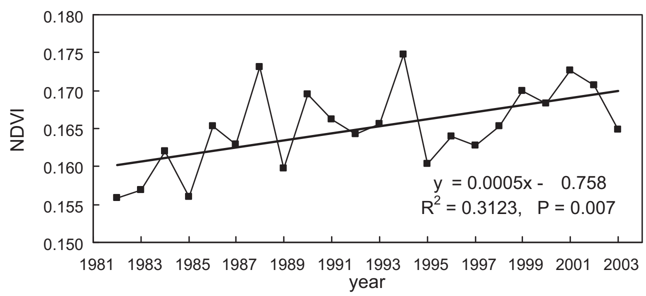

Fig. 5. Annual average NDVI of Qinghai–Tibet Plateau during 1982–2003.

3. Results

3.1. Vegetation dynamic trend during 1982–2003

During the study period, vegetation activity in Qinghai–Tibet Plateau was generally increasing. Through linear regression analysis, it could be concluded that there was a significant upward trend of the annual average NDVI of Qinghai–Tibet Plateau during 1982–2003, with the P value of 0.007 (Fig. 5). In details, the annual average NDVI of the whole plateau reached the top in 1994, and showed substantial decline in 1989 and 1995, respectively; then after 1995, the upward trend continued until 2001.

Moreover, there were distinct differences in the change trends and fluctuations of annual average NDVI among various vegetation types (Table 1, Fig. 6). During 1982–2003, six kinds of vegetation types showed upward trend with the only one downward trend for broad leaf forest. In details, crop had the most significant upward trend (P = 0.002) with comparatively large fluctuations, which was related to the increasing agricultural activities (Liang et al., 2007); meadow and steppe also showed a significant upward trend with comparatively large fluctuations (P = 0.007 and 0.008, respectively), which might be due to the high sensitivity of grassland to climate change in the plateau (Yang and Piao, 2006), and overgrazing in the 1990s also exacerbated the high fluctuations of annual average NDVI of grassland (Liang et al., 2007); desert and shrub experienced the upward trends with comparatively small fluctuations, passing the significance test of 0.05 level, which resulted from the warm–dry trend of climate change in northwestern Qinghai–Tibet Plateau (Yu and Xu, 2009), and the low fluctuation might be due to their low NDVI value; and two forest vegetations showed the non-significant change trends with comparatively high fluctuations, which was related to the increased human activities, and climatic heterogeneity in mountainous areas with low elevation resulted from terrain differentiation (Zhou et al., 2007).

3.2. Spatial differentiation of vegetation dynamic trend

Applying the linear regression analysis to all the pixels, the results showed a distinct spatial differentiation of the linear trend of vegetation dynamics during 1982–2003 in Qinghai–Tibet Plateau, which was represented as the increasing in the west and the decreasing in the east (Table 2, Fig. 7). In sum, 82.39% of the plateau experienced the upward trend of vegetation dynamics, with 25.25% passing the significant test of 0.05 level, which mainly distributed in the western, southern, northern and part of southeast edge of Qinghai–Tibet Plateau. This was in accordance with what reported by Fang et al. (2004). In details, there was Pamirs in the west of the plateau that was inaccessible (Yu et al., 2009), and the significant upward trend of vegetation dynamics was related with the warm trend of climate change; the increased vegetation activities in southern and northern parts of the plateau were mainly due to the warming–wetting trend of local climate (Yu and Xu, 2009).

Meanwhile, there was about 1% of the plateau showing the significant decreasing in annual average NDVI, which mainly distributed in the hinterland, Qinghai Lake, Qaidam Basin, Hexi Corridor, Ali region and the southeastern edge of the plateau. And 16.67% of the plateau experienced the non-significant decreasing in annual average NDVI, distributing in the northwestern, southeastern and middle part of the plateau. It was convinced that the decreasing of vegetation activities in the plateau was the result of human disturbances and natural environmental changes. On one hand, the warming–drying trend of climate change in the hinterland and northwest of the plateau resulted in the degradation of grassland (Wang et al., 2004); On the other hand, natural disturbances of climate change to vegetation dynamics were exacerbated by such increased human activities as overgrazing (Fan et al., 2005).

In terms of various vegetation types, there were also distinct differences among the spatial differentiation of their change trends (Table 2). In details, forest in the plateau experienced great degradation with more than 50% of broad leaf forest and 35% of needle leaf forest showing downward trend, while there was more than 10% of needle leaf forest showing significant increase. This resulted in the azonal characteristics of vegetation dynamics in the southeast of the plateau. Among all the vegetation types, desert had the highest area ratio showing upward trend, with more than 90% increase and 31.61% significant increase. The downward trend of desert vegetation mainly distributed in the northwest of the plateau, which resulted from the warming–drying trend in local climate change (Yu and Xu, 2009). As to steppe, meadow and shrub, far more pixels experienced the upward trend than downward trend, and significant increasing mainly occurred in Hexi Corridor and humid areas of southern Tibet, with vegetation degradation distributing in Ali area and hinterland of the plateau. Due to the increased intensity of agricultural activities in Qinghai–Tibet Plateau, over 80% of agricultural vegetation showed upward trend with 36.4% experiencing significant increase.

3.3. Consistency of future vegetation dynamic trend

Although there was distinct decrease of Hurst Exponent of annual average NDVI time series from west to east in Qinghai–Tibet Plateau (Fig. 8), Hurst Exponent in most of the plateau was bigger than 0.5, which referred to the high consistency of vegetation dynamic trends after the study period in Qinghai–Tibet Plateau. There was only 2.91% of the plateau showing inconsistency of future vegetation dynamic trend, which mainly distributed in hinterland, Hexi Corridor and eastern of the plateau. It was convinced that the inconsistency was mainly due to climate change of warming and drying after late 1990s, and the intensifying of human activities such as urbanization and overgrazing. Furthermore, among the areas with the inconsistency, 73.41% experienced non-significant increase of vegetation dynamics during 1982–2003, with 21.12% non-significant decrease, which meant that the inconsistent areas hardly showed significant vegetation change.

Table 1
Standard deviations of annual average NDVI for each vegetation type in Qinghai–Tibet Plateau during 1982–2003.

Needle leaf forest	Broad leaf forest	Shrub	Desert	Steppe	Meadow	Crop
0.0085	0.0114	0.0057	0.0045	0.0059	0.0068	0.0076

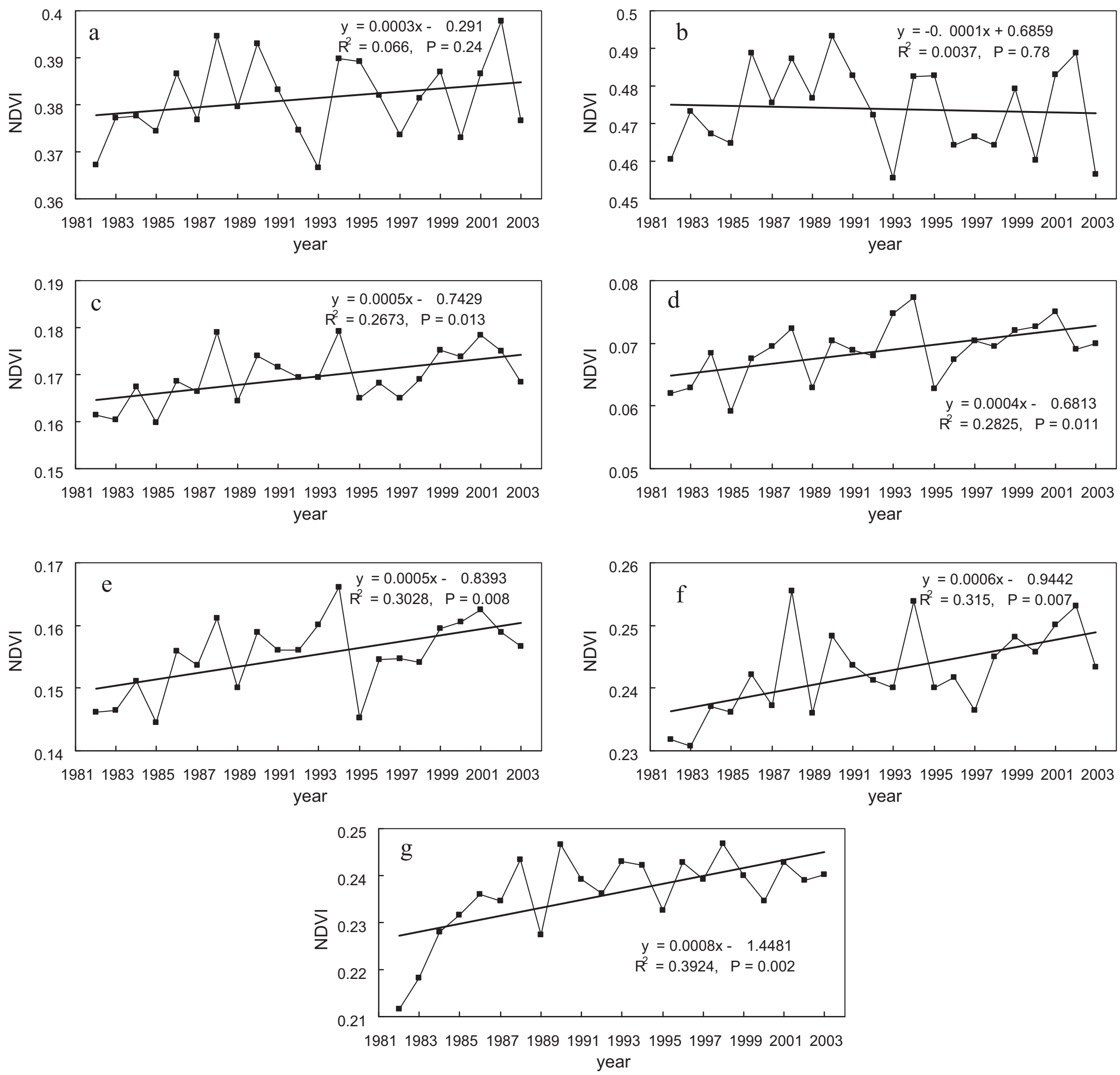

Fig. 6. Annual average NDVI of different vegetation type in Qinghai–Tibet Plateau during 1982–2003: needle leaf forest (a), broad leaf forest (b), shrub (c), desert (d), steppe (e), meadow (f) and crop (g).

The high consistent areas with *H* value over 0.8 mostly located in northwestern and southern of the plateau, which might be due to their relatively stable natural conditions in the northwest, and the warming–wetting trend of climate change in the south, both leading to the same increasing trend of vegetation activities as usual; While the low consistent areas with *H* value between 0.5 and 0.6, mainly distributed in the eastern and southeastern of the plateau, which indicated the sensitivity of vegetation dynamics to climate change in the moisture transition zone from southeast to northwest of the plateau.

In terms of vegetation types, the *H* value for all the types were greater than 0.5 (Table 3), which referred to the consistency of vegetation dynamic trends in the future for each vegetation type as a whole. In details, desert had the highest *H* value, because it mainly distributed in the northwest of the plateau where was one of the most weakly affected areas by human activities in the world.

Table 2
Area ratio of change trend for each vegetation type in Qinghai–Tibet Plateau during 1982–2003 (%).

	Significant decrease	Non-significant decrease	Non-significant increase	Significant increase
The whole plateau	0.94	16.67	57.14	25.25
Needle leaf forest	2.96	32.83	50.28	13.93
Broad leaf forest	2.63	48.15	45.68	3.53
Shrub	0.81	15.36	63.13	20.70
Desert	0.13	9.80	58.46	31.61
Steppe	0.76	15.23	58.71	25.29
Meadow	1.63	19.12	51.79	27.47
Crop	1.30	15.30	47.00	36.40

Significant and non-significant referred to the significance test of 0.05 level.

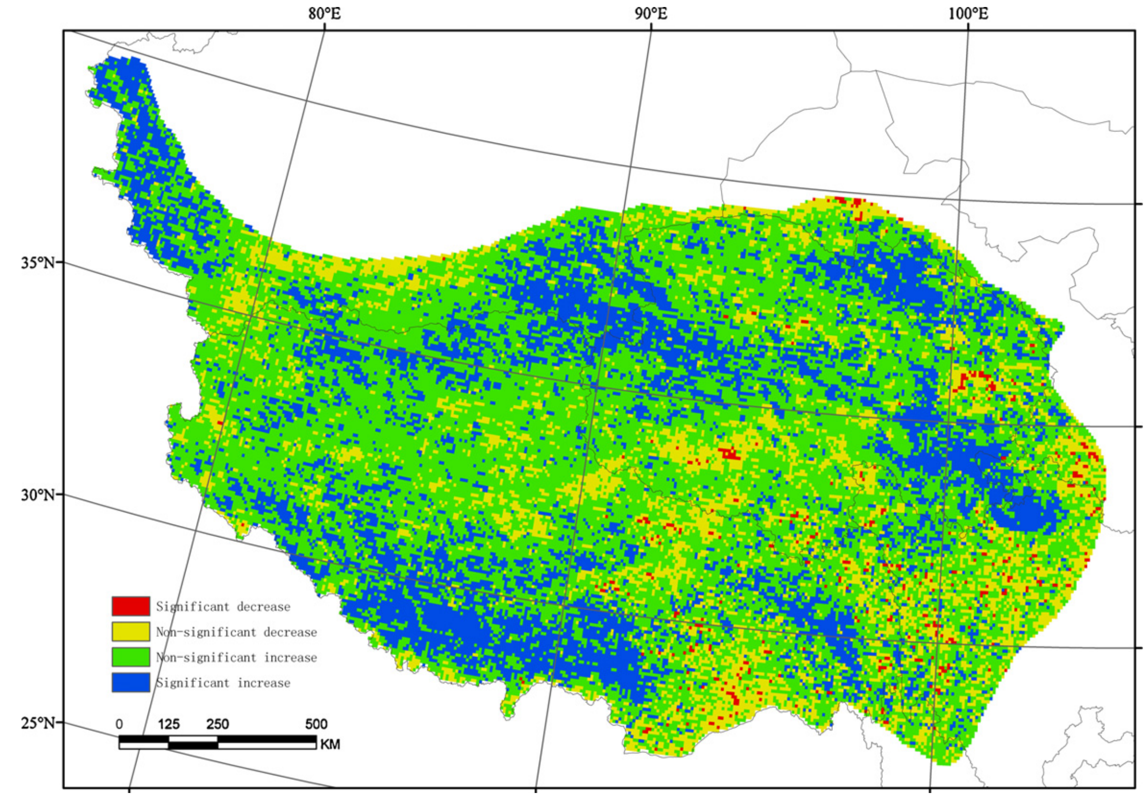

Fig. 7. Spatial distribution of vegetation dynamic trend in Qinghai–Tibet Plateau during 1982–2003.

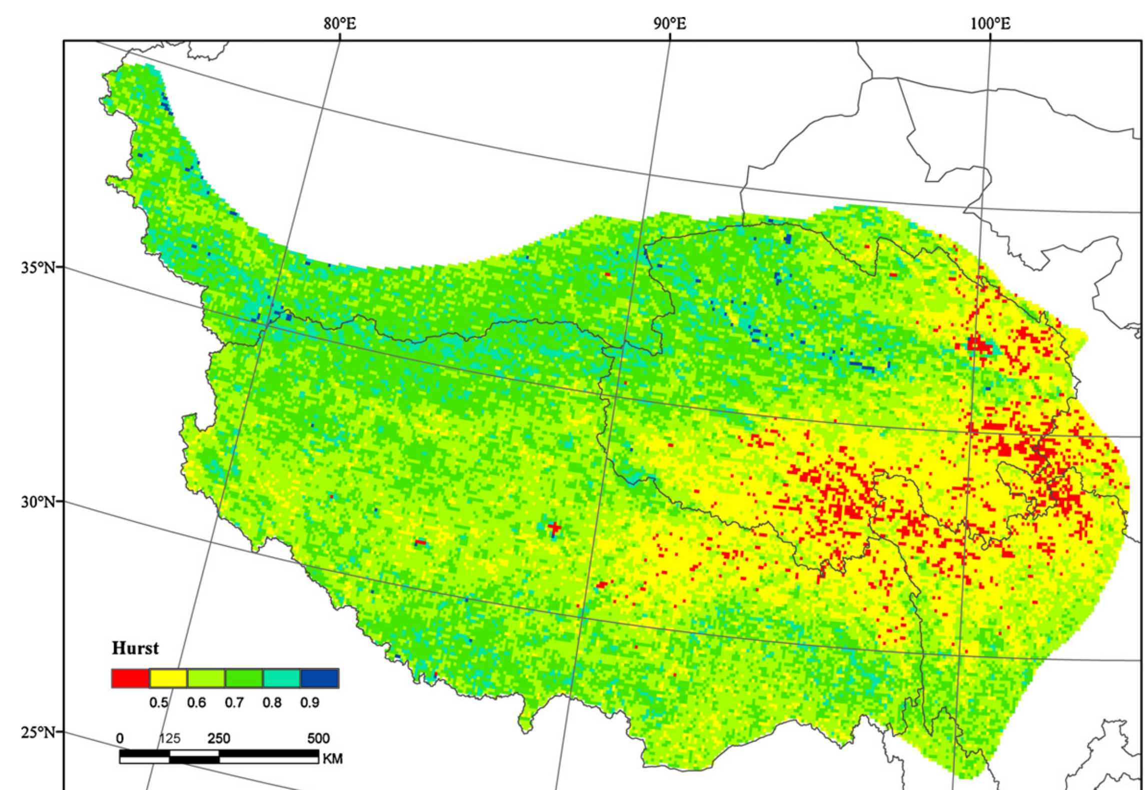

Fig. 8. Spatial distribution of Hurst Exponent of annual average NDVI time series in Qinghai–Tibet Plateau during 1982–2003.

Table 3
Hurst Exponent of annual average NDVI time series for each vegetation type in Qinghai–Tibet Plateau during 1982–2003.

Needle leaf forest	Broad leaf forest	Shrub	Desert	Steppe	Meadow	Crop
0.635	0.652	0.652	0.748	0.657	0.611	0.726

Vegetation activities of desert would keep improving since it was sensitive to precipitation (Zhou et al., 2007) and there was not significant change of precipitation in the west of the plateau (Fan et al., 2008), in addition to the relatively stable natural environment with cold weather. Needle leaf forest and meadow had the lowest H value referring to the weak consistency. In general, vegetation dynamic trend of needle leaf forest was affected by both the climate transition of warming and wetting in Longitudinal Range-Gorge Region of the plateau and the increased human activities in mountain areas with low elevation. And meadow mainly distributed in climate transition zone of moisture from northwest to southeast of the plateau, where elevation was also low with extensive human activities.

4. Discussion

4.1. Validation of R/S analysis

It was necessary to detect the validity of R/S analysis to ensure that the estimated Hurst Exponent was suitable for the trend analysis of vegetation dynamics, since it was the first time for the method of R/S analysis to be applied with AVHRR–NDVI time series. The common method used to detect the validity of R/S analysis was randomly reordered test. The main procedures were to randomly reorder the original time series and to calculate the new Hurst Exponent. It was assumed that the randomly reordered time series was a random sequence, and therefore the new Hurst Exponent should be equal to 0.5 according to the definition of the indicator (Hurst, 1951). Thus, whether the Hurst Exponent of new generated time series was close to 0.5 would be taken as the criterion to detect the validity of R/S analysis.

It was contrasted between Hurst Exponents for original and randomly reordered annual average NDVI time series of each pixel in Qinghai–Tibet Plateau during 1982–2003 (Fig. 9). There were 47,925 pixels in all taken into account in the contrast. As shown in Fig. 9, most of Hurst Exponents of original time series were above 0.5, and mainly lied between 0.6 and 0.8; while the Hurst Exponents of randomly reordered time series were more close to 0.5, centering around the value of 0.55. Although the Hurst Exponents of new time series were not all equal to 0.5, it was clear that most new Hurst Exponents were smaller than the original ones, since the majority of the pixels lied below the line of 45°, which indicated that the generated time series was closer to random walk process than the original time series. Therefore, it could be concluded that the reordering of time series had broken the structure of original time series in a certain extent, which confirmed the validity of R/S analysis applied to AVHRR–NDVI dataset in Qinghai–Tibet Plateau.

4.2. Influence of topographic factor

It was convinced that vegetation dynamics were driven by climate change, especially the change of temperature and precipitation. Moreover, the spatial patterns and associated dynamics of climate factors were highly influenced by the complicated topography in Qinghai–Tibet Plateau (Zhang and Gao, 2006). Topography was more and more regarded as the limiting factor on vegetation dynamics at a broad scale (Fu et al., 2004, 2009). However, the limiting factor was often ignored in the correlation analysis between vegetation dynamics and associated changes of environmental factors, which resulted in the overall bias of the correlation fitting.

The spatial patterns of Hurst Exponent in Qinghai–Tibet Plateau were also highly related to the topography (Fig. 10). In the study, there were 47,925 pixels with the resolution of 8 km × 8 km counted in all. The pixels were classified into 8 elevation zones with an interval of 1000 m, and the Hurst Exponent in each elevation zone was acquired through calculating the average Hurst Exponent of all the pixels in the zone. The results showed a distinct variation feature of 'high-low-high' for the change of Hurst Exponent in accordance with elevation rising. In details, Hurst Exponent showed high value in elevation zones below 3000 m, low value in elevation zones between 3000 m and 5000 m, and high value in elevation zones above 5000 m, which generally well fitted with the U-curve trend.

Furthermore, since it was the average value of the pixels in the zone, Hurst Exponent in each elevation zone was determined fully by both the dynamic trend consistency and the area ratio of various vegetation types. As shown in Table 3, there was high consistency for desert and crop, middle consistency for shrub and steppe, and low consistency for forest and meadow in Qinghai–Tibet Plateau. Through Fig. 10, it could be found that, along with elevation rising from 1000 m to 3000 m, the area ratio structure of vegetation types shifted from the single type of forest to the combination of various vegetation types, especially the increasing of desert and agricultural vegetation, which leaded to the increase of average Hurst Exponent in each elevation zone. In the elevation zone of 3000–5000 m, it was the area ratio decreasing of desert and agricultural vegetation, and increasing of steppe, shrub and meadow that resulted in the decreasing of the average Hurst Exponent in the zone. Moreover, when the elevation was greater than 5000 m, the area ratio of steppe and shrub decreased rapidly, along with the increasing of desert and non-vegetation area, leading to the increasing of vegetation dynamic consistency.

Therefore, it could be concluded that, topography had significant effect on regional climate through altering the spatial patterns of local hydrothermal conditions, while the latter was one of the main controlling factors on the spatial distribution of vegetation types. Because there were great differences in the response to climate change among various vegetation types, the spatial differentiation of vegetation dynamics were formed among different terrain areas. Therefore, in the case study of climate–vegetation change model with such a complicated terrain as Qinghai–Tibet Plateau, it was helpful to analyze the influence of topographic factor on vegetation change, so as to acquire more understanding of climate–vegetation change mechanism, although it was often ignored in current studies (Amanda et al., 2005).

4.3. Limitations and future research directions

Compared with various case studies on vegetation dynamics, which considered future change trend of vegetation dynamics was the same as that in the study period, it was a great advance in this case study to quantify the future vegetation dynamic trend using Hurst Exponent, although the case study also agreed with the close correlation between vegetation dynamic trends in the future and in the past. However, the proposed R/S analysis with Hurst Exponent in the case study could not answer the following question: how long would the anticipated vegetation dynamic trend continue in

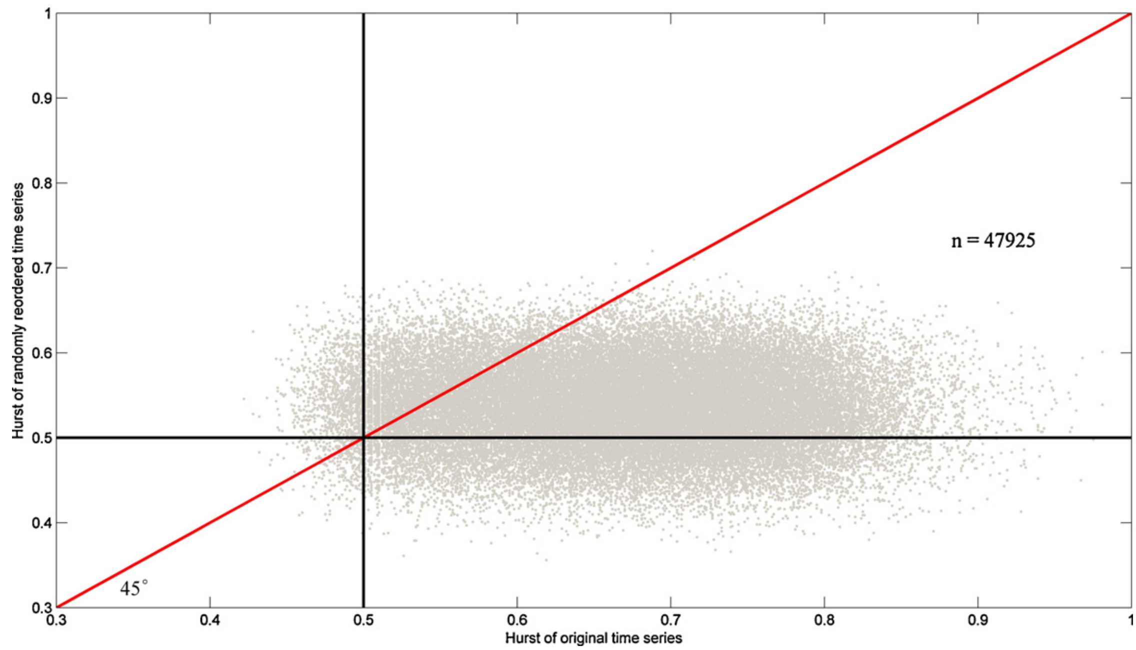

Fig. 9. Contrast between Hurst Exponents of original and randomly reordered annual average NDVI time series in Qinghai–Tibet Plateau during 1982–2003.

the future? It was more important to point out the continuing time in forecasting future vegetation dynamics.

Therefore, further case studies and theoretical analysis should be paid attentions to detailed process of future vegetation dynamics. On the basis of quantifying future change trend, it was in great need to indicate the duration of anticipated vegetation dynamics, to find out the abrupt turning point of vegetation dynamics in the future, and to judge whether the turning point indicated a mutation. All the four tasks mentioned above made up of a full and detailed depiction of the process of future vegetation dynamics, which was essential to human countermeasures associated with vegetation change.

Although R/S analysis proposed in this study could only quantify future vegetation dynamic trend, and could not respond to the change duration, there had been respectable progresses on the mutation detection of vegetation dynamics. For example, Verbesselt et al. (2010) proposed the method of Breaks For Additive Seasonal and Trend (BFAST) to detect the break points of forest change in south eastern Australia. BFAST integrated the decomposition of NDVI time series into trend, seasonal and remainder

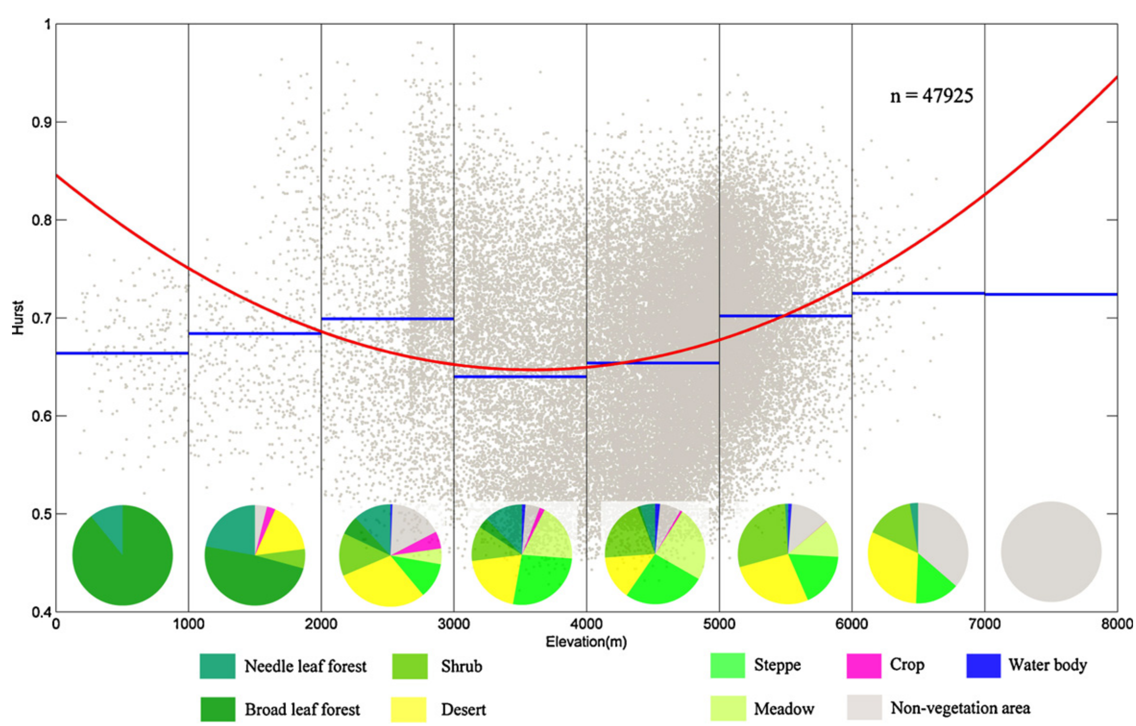

Fig. 10. Contrast among Hurst Exponent of annual average NDVI time series for each elevation zone in Qinghai–Tibet Plateau during 1982–2003.

components, and it was proposed that break points in the trend component indicated the human or natural disturbances, with break points in the seasonal component for phonological change (Verbesselt et al., 2010). Thus, it would be the key direction to integrate R/S analysis with mutation detection approaches in quantifying future vegetation dynamic trend.

It is convinced that as an indicator of terrestrial ecosystem change, vegetation dynamics result from climate change and human activities. Thus, although the impact of topography on vegetation dynamic trend was analyzed in this case study, far more driving forces associated with vegetation change should be focused, especially human activities and the change of temperature and precipitation, which would be a great help to the fully understanding of vegetation change process.

In addition, due to its long temporal span, GIMMS–NDVI dataset is seemed as the only available one for long time series detection of vegetation dynamics at large scales. However, the spatial resolution of 8 km makes it a great challenge to validate the accuracy of remote sensed vegetation coverage, although it is acknowledged that the spatial resolution will get more and more coarse along with the enlarging of the study area. As a result, it is in great need to develop a new remote sensing dataset with fine resolution and long time series for vegetation dynamics monitoring and assessment.

5. Conclusions

Taking Qinghai–Tibet Plateau, which had the most sensitive vegetation change under the impact of climate change in the world, as the study area, vegetation dynamic trends during 1982–2003 and after the study period were quantified using Hurst Exponent with the application of GIMMS–NDVI data. The results showed that, in the past 22 years, the plateau experienced an uptrend as a whole with 82.39% of vegetation getting better, while nearly 50% of broad leaf forest was in the process of degradation. Among all the 7 kinds of vegetation types, both broad leaf forest and needle leaf forest had the largest standard deviation of NDVI time series which indicated the significant fluctuation of forest vegetation, with desert for most stable vegetation in the study period. According to the R/S analysis, there was high consistency of future vegetation dynamic trends with the former trend in the study period in the plateau, which meant that forest would continue to degrade with desert and shrub keeping improved. The inconsistent areas were mainly meadow and steppe located in the middle or east of the plateau. However, although the Hurst Exponent and R/S analysis proposed in this study was proved to be useful to quantify future vegetation dynamic trend, it failed to detect the duration and mutation of anticipated change, and further studies should be directed to the very topic.

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