Spatiotemporal variation of vegetation dynamics and correlations with climatic factors in the Tibetan Plateau, China

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Abstract. The Tibetan Plateau has been recognized as one of the most sensitive areas responding to climate change, and has becomes a hotspot for coupled studies on terrestrial ecosystem variation and climate change. Leaf area index (LAI) is a key indicator that reflects vegetation dynamics and has been widely used to analyze the responses of vegetation to climate change. In this study, the spatiotemporal variation of LAI in the growing season and its correlations with climatic factors were analyzed. The results showed that the spatial pattern of LAI decreased from southeast to northwest. In terms of the temporal trend of LAI, 85% of the total study area experienced an increased trend. Additionally, 74% of the whole plateau will experience an improved vegetation growth in the future. Furthermore, temperature, precipitation and solar radiation all showed positive correlations with LAI for most of the study area. Our results effectively revealed the variation of LAI and its correlations with climatic factors. However, grassland in the plateau have been shown to have a greater and more rapid response to climatic fluctuations. Therefore, more managements should be made by local governments to improve the fragile environment, especially for areas with a decreasing LAI trend.

1. Introduction
As a key connectivity among atmosphere, pedosphere, and hydrosphere, vegetation plays an irreplaceable component in atmosphere adjustment, soil conservation, and the maintenance of climatic and ecosystem stability [1,2]. Due to the critical role of vegetation coverage in regulating the balance of regional ecosystems [1,3,4], the variation of vegetation dynamics has been recognized the basis of the protection of the ecological environment [3,5].

With wide coverage and long time series span, freely remote sensing data with high temporal resolution has recognized as the most important data source for monitoring the variation of vegetation dynamics over long time period at large scales [6-8]. Widely applied as the parameters of vegetation dynamics, vegetation index such as normalized difference vegetation index (NDVI) has been most widely used as an effective index for monitoring vegetation dynamics [1,9]. Based on the National Oceanic and Atmospheric Administration (NOAA) Advanced Very High-Resolution Radiometer (AVHRR) NDVI, Duan et al [10] found a significant increasing trend of NDVI for most part of Xinjiang Province during 1981-2006. Moreover, the relationships between NDVI and climatic factors have also
been recognized to reflect the responses of vegetation dynamics to climate change [11-13]. Alpine grassland in the Tibetan Plateau covers 34.3% of the total grassland in China [14], and plays a key role in global carbon cycles [15]. Due to the fragile ecological environment and sensitivity to climate change [16], the Tibetan Plateau act as a suitable region for the study of vegetation dynamics and its correlation with climatic factors. Numerous research have been explored vegetation dynamics in the plateau by means of NDVI and net primary productivity (NPP) as an indicator. Fang et al [17] found that NDVI in the plateau displayed an increasing trend during 1982-1999. Peng et al [3] put forward that the plateau experienced a significant increasing trend of NDVI during 1982-2003 based on linear regression analysis. Pan et al [18] revealed that annual grassland NDVI slightly increases with fluctuation during 1982-2013. In contrast, Wang et al [19] observed that NPP in the plateau showed a decreasing magnitude of 0.16 Tg C a⁻¹ during 2000-2012. In terms of methodology, linear regression analysis method was mostly applied to analyze vegetation dynamics due to its simplicity and robustness [20]. However, mutation would be smoothed in the method. Moreover, the trend of vegetation dynamics is usually not a linear trend at the background of climate change and intensive anthropogenic activities occurred simultaneously, therefore, a non-linear trend in this method is unable to detected [3]. In addition, the variation trends in the future seems more significant than that of study period, because the former could really respond to vegetation change in the future [3] under the background of climate change. Unfortunately, few studies have explored the variation trend in the future [3,21].

In the present study, we took the Tibetan Plateau as a study region with the objectives of (1) to analyze the variation of grassland LAI in growing season during period 1982-2013 and after 2013; and (2) to understand the relationship between LAI and climatic factors. Our results improved the understanding of physiological and biophysical processes further, and will motivate local government to focus ecological protection and/or restoration on the plateau. Moreover, our findings could contribute to ecological construction achievements in the plateau at the background of climate change and intensive anthropogenic activities.

2. Materials and methods

2.1. Study area

The Tibetan Plateau (26°00′12″ N — 39°46′50″ N, 73°18′52″ E — 104°46′59″ E) lies in the southwest
of China, covering nearly 2.5 million square kilometers with an average elevation of over 4000 m (figure 1(a)). It is the largest plateau and most extensive highland in the world, and known as roof of the world [16]. The plateau has profound thermal and dynamical effects on climate and atmospheric circulation because of its unique topography and geographical location. The major climate features in the plateau were characterized by low air temperature, strong solar radiation and clear demarcation [22]. Mean annual temperatures and mean annual precipitation ranging from −5°C to 12°C and more than 800 mm to less than 200 mm, respectively [23], and the vegetation types were dominantly by alpine meadows, alpine steppes, shrubs and forests (figure 1(b)).

2.2. Data sources

Datasets used in this study include Leaf area index (LAI), defined as one-half of the total leaf area per unit ground surface [24], climate data, and vegetation type data. Global Land Surface Satellite (GLASS) LAI product with a spatial and temporal resolution of 0.05° and 8 days respectively from 1982-2013 were applied in this study. The LAI values of the dataset were retrieved by general regression neural networks, and provides much better quality and accuracy than other LAI datasets such as CYCLOPES LAI dataset. To analyze the correlation between LAI and climatic factors, site observed temperature, precipitation and solar radiation from 1982 to 2013 were download from the China Meteorological Data Sharing Service System. It has been illustrated that the missing and false data in this dataset has been excluded [2]. Kriging spatial interpolation method was applied to climate data, and then a spatial resolution of 0.05° were then output to consistent with the LAI dataset. Because the dominant vegetation type in the plateau was grassland, and our purposes were to explore the variation of grassland LAI dynamics and its correlation with climatic factors, therefore, pixels with non-grassland (e.g., forests) in growing season were masked out based on vegetation type dataset in the plateau (figure 1(b)). Additionally, the growing season was defined from May to October according to our previous publish [25], then the mean LAI of each year for growing season were applied to further analysis.

2.3. Methods

The magnitude of LAI variation was calculated based on Theil-Sen Median analysis. It is a robust statistical method [26] to estimate noisy variable changes and/or variable changes with short time series [27]. The Theil-Sen Median trend for each pixel was calculated as follows:

\[
\text{slope}_i = \text{Median}\left(\frac{LAI_m - LAI_n}{m-n}\right) \text{ for } i = 1, \ldots, N
\]  

(1)

where \(\text{slope}_i\) is the magnitude of LAI variation at \(i\) pixel; \(LAI_m\) and \(LAI_n\) are the LAI values at times \(m\) and \(n\) \((m > n)\), respectively.

To test the significance of the magnitude, the Mann–Kendall (M-K) method, a non-parametric statistical test [28], was applied. It has been widely applied in analyzing hydrological and meteorological time series [1]. The M-K was calculated as equations (2)-(5).

\[
S_{LAI} = \sum_{q=1}^{m-1} \sum_{p=q+1}^{m} \text{sgn}(LAI_p - LAI_q)
\]  

(2)

where \(m\) is the number of data points, \(LAI_p\) and \(LAI_q\) are the data values at times \(p\) and \(q\) \((p > q)\), respectively, and \(\text{sgn}(LAI_p - LAI_q)\) is the sign function

\[
\text{sgn}(LAI_p - LAI_q) = \begin{cases} +1, & \text{if } LAI_p - LAI_q > 0 \\ 0, & \text{if } LAI_p - LAI_q = 0 \\ -1, & \text{if } LAI_p - LAI_q < 0 \end{cases}
\]  

(3)

The test statistic \(Z\) is calculated using equation (4). It has been illustrated that the statistic \(Z\) is nearly normal distribution when the sample size \(m\) greater than 8 [28]. The sample size \(m\) in this study was equal to 32, and trends were tested at \(\alpha = 0.05\).
where \( Z = \begin{cases} \frac{S_{LAI} - 1}{\sqrt{\text{Var}(s)}}, & \text{if } S_{LAI} > 0 \\ 0, & \text{if } S_{LAI} = 0 \\ \frac{S_{LAI} + 1}{\sqrt{\text{Var}(s)}}, & \text{if } S_{LAI} < 0 \end{cases} \) (4)

where \( \text{Var}(s) \) is calculated as follows:

\[
\text{Var}(S) = \frac{m(m-1)(2m+5)-\sum_{i=1}^{t} k_i (k_i-1)(2k_i+5)}{18}
\] (5)

where \( t \) is the number of tied groups and \( k_i \) denotes the number of ties of extent \( i \).

To identify the consistency of LAI variation between the study period and after the study period, the Hurst exponent based on R/S analysis was applied. The exponent has been widely applied in many fields such as climatology, hydrology, economics, vegetation dynamics, geo-chemistry and geology \([1,21,29]\). The exponent was calculated as follows:

- Divide the time series \( \{LAI(i)\} (i=1, 2, \ldots, m) \) into \( i \) sub series \( S_{LAI(n)} \), and for each series \( n = 1, \ldots, i \).
- Define the mean sequence of the time series,

\[
LAI(i) = \frac{\sum_{n=1}^{i} LAI_n}{i} \quad i = 1, 2, \ldots, m
\] (6)

- Calculate the range sequence,

\[
S_{LAI(n,i)} = \sum_{n=1}^{i} (LAI_n - \bar{LAI}(i)) \quad 1 \leq n \leq i
\] (7)

- Create the range sequence,

\[
R_i = \max_{1 \leq n \leq i} S_{LAI(n,i)} - \min_{1 \leq n \leq i} S_{LAI(n,i)} \quad i = 1, 2, \ldots, m
\] (8)

- Create the standard deviation sequence,

\[
S_i = \sqrt{\frac{\sum_{n=1}^{i} (LAI_n - LAI(i))^2}{i}} \quad i = 1, 2, \ldots, m
\] (9)

- Calculate the Hurst exponent,

\[
\frac{R_i}{S_i} = c t^H
\] (10)

where \( H \) is the Hurst exponent, and calculated based on the following fitting equation using the least squares method.

\[
\log \left( \frac{R_i}{S_i} \right) = a + H \times \log(m)
\] (11)

According to previous study \([30,31]\), the range of \( H \) value is from 0 to 1. When the \( H \) value is equal to 0.5, it means the trend of LAI after the study period would be unrelated with that of the study period. However, when the \( H \) value is greater or lower than 0.5, it means that the LAI trend in the future is consistent or inconsistent with the study period, respectively.

To observe the relationship between LAI and climatic factors (e.g., temperature), partial correlation analysis, which excludes the effects of other variables and has been widely used to explore vegetation–climate interactions \([32]\), was applied. Moreover, the relationship was tested at a significance level of \( \alpha = 0.05 \).

3. Results

3.1. Spatial pattern of LAI
The spatial pattern of average LAI and its standard deviation for the 32 years from 1982 to 2013 are presented in figure 2. The spatial distribution of average LAI was regional difference, showing a decreasing trend from southeast to northwest. The highest value of LAI distributed in east of the plateau, with values higher than 4.46 m²/m², accounted approximately 8.99% of the total area. In contrast, average LAI is usually lower than 1.00 m²/m² was distributed in northwest of the plateau and accounted more than 21% of the total area. For the remaining areas, LAI varied from 1 to 4.46 m²/m², and mostly occurred in middle and southwest of the plateau (figure 2(a)). The spatial distribution of standard deviation is similar to that of mean LAI (figure 2(b)). The lowest standard deviation with values lower than 0.42 m²/m² were found in west of the plateau, while the highest values occurred in south of the plateau, with values mostly higher than 1.4 m²/m². For the remaining areas, the standard deviation mostly varied between 0.42 and 1.40 m²/m².

**Figure 2.** Spatial pattern of average LAI (a) and corresponding standard deviation (b) in the Tibetan Plateau over 1982-2013.

3.2. Temporal trend of LAI from 1982 to 2013

**Figure 3.** Frequency distribution of LAI trends in the Tibetan Plateau during 1982-2013.
Temporal trend of LAI in the growing season was illustrated in figures 3 and 4. During the study period (1982-2013), increasing trend of LAI accounted 85.60% of the total plateau, of which 44.61% displayed a significant positive trend \((p < 0.05; \text{figure 3})\). Significant positive trend were mainly occurred in northeast and southwest of the plateau (figure 4(b)). The magnitudes of increasing LAI mostly ranged from 0 to 0.1 \(\text{m}^2/\text{m}^2/\text{a}\) (figure 3). In contrast, 14.40% of the plateau showed a negative trend, of which 1.77% showed a significant decreasing trend (figure 3). The decreasing magnitude of growing season LAI in the plateau mostly occurred at -0.03—0 \(\text{m}^2/\text{m}^2/\text{a}\), and scattered in west and southeast of the plateau (figure 4(a)).

**Figure 4.** Trends of LAI in growing season within the plateau between 1982 and 2013 (a). Areas with significant \((p < 0.05)\) and very significant \((p < 0.01)\) variation are also displayed (b). Positive value means increased LAI and vice versa; DS and IS indicate significantly decreased and significantly increased LAI trend, respectively, while DVS and IVS indicate very significantly decreased and very significantly increased LAI trend, respectively.

### 3.3. Consistency of LAI trend analysis

As shown in table 1, areas with Hurst exponents higher than 0.5, accounted 77.06% of the whole plateau, and they were mostly found in southwest and middle of the plateau, suggesting a consistent trend of LAI variation between the study period and after the study period. Approximately 23% of the total pixels displayed that the Hurst exponents were lower than 0.5, and they mostly found in northwest and southeast of the plateau (figure 5(a)), suggesting an inconsistent trend of LAI variation between the study period and after the study period.

| Hurst exponent | Percentage (%) | Variation types | Percentage (%) |
|----------------|----------------|-----------------|----------------|
| 0 - 0.1        | 0.35           | SI              | 68.55%         |
| 0.1 - 0.3      | 3.41           | USID            | 17.05%         |
| 0.3 - 0.5      | 19.18          |                 |                |
| 0.5 - 0.7      | 43.68          | SD              | 8.68%          |
| 0.7 - 0.9      | 31.49          |                 |                |
| 0.9 - 1        | 1.89           | USDI            | 5.72%          |

**Table 1.** Hurst exponent and sustainability of LAI in the growing season across the plateau during 1982 — 2013.
Moreover, trends result from the Mann-Kendall method was superimposed with the Hurst exponent results to yield the coupled information of variation in trends sustainability. The coupling results were analyzed in four cases, namely (1) sustainable improvement (SI): a positive variation trend with the Hurst exponent higher than 0.5; (2) unsustainable and changed from improvement to degradation (USID): a positive variation trend with the Hurst exponent lower than 0.5; (3) sustainable degradation (SD): a negative variation trend with the Hurst exponent higher than 0.5; (4) unsustainable and changed from degradation to improvement (USDI): a negative variation trend with the Hurst exponent lower than 0.5. The results from table 1 shows that the sustainable area accounted 77.23% of the total, of which 68.55% was SI, and 8.68% was SD. The SI of LAI was mostly found in southwest and east of the plateau, while the SD area was mostly located in northwest of the plateau (figure 5(b)). Approximately 22.77% of the total area showed unsustainable, of which the variation of LAI changed from improvement to degradation account for 17.05% (table 1), and they mainly scattered in north and southeast of the plateau. The variation of LAI changed from degradation to improvement account for 5.72%, and they mostly scattered in northwest and middle of the plateau. Our results indicate that approximately 74.27% of the study region displayed an improved LAI, while 25.73% of the study region undergoing a degradation trend in the future.

3.4. Correlations between LAI and climatic factors

Climatic factors displayed a positive relationship with LAI (figure 6). Approximately 76.28% and 70.73% of the total area exhibited positive relationships between LAI and temperature as well as precipitation, respectively. In addition, more than 11% of the total displayed significant positive correlations between LAI and temperature as well as precipitation ($p < 0.05$). The positive relationship between LAI and temperature mainly occurred in east and middle of the Tibetan Plateau, while for precipitation, they mostly found in middle and southwest of the plateau. The positive partial correlation coefficient between LAI and temperature and precipitation was mostly distributed between 0 and 0.5 (figures 6(c) and 6(f)). In terms of the correlation between LAI and solar radiation, about 63.34% of the total indicated positive, but only 5.76% of the total showed significant ($p < 0.05$; figure 6(i)). The positive relationships were mostly distributed in southwest of the plateau, while the negative relationships were mainly occurred in southeast of the plateau. The positive partial correlation
coefficient between LAI and solar radiation was mostly distributed between 0 and 0.3, while the negative partial correlation coefficient was mainly ranges from -0.3 to 0 (figure 6(i)).

Figure 6. Partial correlation coefficients and the spatial distribution of significant relationship between LAI and (a,b) temperature, (d,e) precipitation and (g,h) solar radiation in the plateau from 1982 to 2013. The corresponding frequency distributions (c,f,i) were also displayed. Data listed within bracket were the ratio of significant pixels at the level of $p < 0.05$.

4. Discussion

4.1. Spatiotemporal variation of LAI
Generally, the spatial distribution of LAI in growing season on the plateau decreasing from southeast to northwest, which was consistence with the spatial pattern of the hydrothermal conditions in the plateau [33]. The highest LAI with value more than 4.46 m$^2$/m$^2$ was displayed in east and southeast of the plateau, and mainly due to monsoons that providing a favorable hydrothermal conditions in growing
season for vegetation growth [16]. In contrast, LAI in northwest was mostly lower than 1 m²/m², which may cause by low temperature and insufficient water supply because of the high elevation and inland location.

Previous studies show that environment conditions in the plateau have changed heavily [34-36]. For instance, climate changes in the plateau have been characterized by increasing temperature and decreasing precipitation [16], which bring a warmer and drier environment for hindering vegetation growth [34]. In addition, anthropogenic activities such as agriculture use, unsustainable practices (e.g., over-logging), urbanization and collection of herb medicines [35-37] were also responsible for the harsh environment that hampered vegetation growth. However, our results revealed that more than 85% of the total displayed an increasing trend of the growing season LAI in the plateau during 1982 — 2013, suggesting little impacts of harsh environment conditions on vegetation growth. Alternatively, the increased LAI for most of the study area may also reflects that vegetation in these areas have their own strategies to adapt the current changing conditions. However, the trend of LAI in west and southeast of the plateau were decreasing during the study period. Therefore, more attentions should be paid and more managements such as local government in adopting policies or projections should be taken to resist harsh environment conditions and to promote vegetation growth in the future.

The Mann-Kendall analysis together with Hurst exponent revealed the future sustainability of the LAI trends in the plateau. Our results illustrated that the Hurst exponent was larger than 0.5 in most of the plateau, which indicated a high consistency of LAI variation after year 2013. Furthermore, among the areas with the consistency, 8.68% experienced consistency degradation, and mainly distributed in hinterland. This may cause by relatively stable harsh environment conditions such as warming-drying climate in the northwest of the plateau [3]. Approximately 22.77% of the total area displaying inconsistency of future LAI trend, which might be due to warming and drying after late 1990s [16,38] and the intensified anthropogenic activities such as overgrazing and urbanization [3].

4.2. Relationship between LAI and climatic factors

Previous studies have illustrated that climatic factors are the critical factors that affect vegetation dynamics [16,39]. Overall, temperature in growing season were positively correlated with LAI, accounted more than 76% of the total, which was consistence with previous studies [16,21]. This may be caused by high temperature that provides a warm environmental conditions for vegetation growth especially for vegetation that growing in high elevation. In addition, the activity of photosynthetic enzymes would be increased by a warmer temperature and then enhanced the capacity of vegetation for photosynthesis [40,41]. Alternatively, high temperature usually promotes the thaw of frozen soil and glacier in the plateau, which provide more water for vegetation growth. The correlations between LAI and precipitation supported this conclusion. More than 70% of the total area displayed that the growing season precipitation have a positive relationship with LAI. This is because grassland usually has a shallow root depth, and the water utilized by grasses usually comes from superficial soil profiles. As such, more precipitation usually results in increase of soil moisture, which can meet water requirements for vegetation growth, especially for areas with a decreasing trend of precipitation [16,19]. More than 65% of the whole area showed a positive relationship between the growing season LAI and solar radiation. This may because sufficient solar radiation supply enough energy for vegetation photosynthesis, which enhanced photosynthesis and promote vegetation growth. Previous studies have illustrated that alpine grassland in the plateau have been shown to have a greater and more rapid response to climatic fluctuations [42]. If grass in the plateau could adapted the fluctuations after responses, more protection and managements should be made for this kind of grassland to avoid unsustainable practices (e.g., over-logging). However, if they cannot, more managements should be made to help them to adapt or replaced them by adapted grassland. Therefore, more managements should be made by local governments to improve the fragile environment to promote vegetation growth.

4.3. Limitations and future research directions

Hurst exponent, served as an index to identify the consistency of variable variation between the study
period and after the study period, has been widely applied in various fields, such as geology, hydrology, geochemistry and climatology to distinguish sustainability of time series data [29]. However, it could not analysis how long the sustainability or unsustainability of the predicted LAI trends would continue into the future, despite in the importance for forecasting future LAI variation. Therefore, it is urgent to determining the duration of LAI trends. Additionally, the variation of LAI was influenced by various factors, such as elevation, soil characteristics (e.g., temperature and water content), CO₂ concentrations, nitrogen enrichment and deposition, and local government policy and planning changes. However, only three climatic factors were included for our study. Therefore, the factors mention above should also be considered in future studies. Although it is acknowledged that the spatial resolution will get more and more coarse along with the enlarging of the study area, the spatial resolution of LAI used in this study made it difficult to validate the accuracy of its variation. Therefore, a new remote sensing dataset with more fine spatial and time resolution and long time series for LAI variation analysis need to develop in the future.

5. Conclusions

the growing season GLASS LAI dataset and climatic gridded data were applied to analysis the spatiotemporal change of LAI and its correlation with climatic factors in the plateau during 1982 — 2013. Our results indicated that the spatial distribution of average LAI was area difference, and showed gradients decreasing from southeast to northwest. In addition, more than 85% of the total study area experienced an increased LAI trend. However, 14.40% of the total area displayed a negative trend, and scattered in west and southeast of the plateau. According to the superimposed of Mann-Kendall analysis and Hurst exponent analysis, more than 77% of the whole area has high consistency of future LAI variation trends with the former trend during the period of 1982-2013, of which 68.55% was sustainable improvement. Additionally, nearly 6% of the total area displayed unsustainable and LAI trend changed from decrease to increase in the future. This meant that more than 74% of the whole plateau will experience an enhanced vegetation growth in the future. Furthermore, temperature, precipitation and solar radiation all showed positive relationship with LAI for most of the study area.

Acknowledgments

This study is funded by the Central Fund Supporting Nonprofit Scientific Institutes for Basic Research and Development (Grant No. PM-zx421-201803-056).

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