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Original Article

Precipitation and anthropogenic activities regulate the changes of NDVI in Zhegucuo Valley on the southern Tibetan Plateau

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Abstract: Whether climate change or anthropogenic activities play a more pivotal role in regulating vegetation growth on the Tibetan Plateau is still controversial. A better understanding on grassland changes at a fine scale may provide important guidance for local government policy and grassland management. Using two of the most reliable satellite NDVI products (MODIS NDVI and SPOT NDVI), we evaluated the dynamic of grasslands in the Zhegucuo valley on the southern Tibetan Plateau from 2000 to 2020, and analyzed its driving factors and relative influences of climate change and anthropogenic activities. Here, the key indicators of climate change were assumed to be precipitation and temperature. The main results were: (1) the grassland NDVI in Zhegucuo valley did not reflect a significant temporal change during the last 21 years. The variation of precipitation during the early growing season (GSP) resembled that of NDVI, and the GSP was positively correlated with NDVI. At the pixel level, the partial correlation analysis showed that 37.79% of the pixels depicted a positive relationship between GSP and NDVI, while 11.32% of the pixels showed a negative relationship between temperature during the early growing season (GST) and NDVI. (2) In view of the spatial distribution, the areas mainly controlled by GSP were generally distributed in the southern part, while those affected by GST stood in the eastern part, mainly around the Zhegucuo lake where most population in Cuomei County settled down. (3) Decreasing NDVI trends were mainly occurred in alpine steppe at lower elevations rather than alpine meadow at higher elevations. (4) The residual trend (RESTREND) analysis further indicated that the anthropogenic activities played a more pivotal role in regulating the annual changes of NDVI rather than climate factors in this area. Future studies should pay more attention on climate extremes rather than the simple temporal trends. Also, the influence of human activities on alpine grassland needs to be accessed and fully considered in future sustainable management.

Keywords: Anthropogenic activities; Climate change; Precipitation; Fencing; Vegetation degradation

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1 Introduction

The responses of terrestrial vegetation growth to climate change and anthropogenic activities and their mechanisms are important scientific issues in global change research, and are also closely associated with the sustainable development of human society (Sun et al. 2022). During past decades, though some of the global vegetation area exhibited a browning trend, more area has generally become greener (Ding et al. 2020a; Feng et al. 2021), with the vegetation growth of China gradually being an outstanding contributor to the global greening (Chen et al. 2019). Climate warming and CO2 fertilization effects are usually assumed to be the key factors driving the greenness (Goetz et al. 2005; Zhu et al. 2016). However, some researchers also proved that anthropogenic activities rather than climate change mainly drove the greening trend in China and India during 2000-2017 (Chen et al. 2019).

As a unique geographic unit, the Tibetan Plateau is recognized as the roof of the world. Among the natural vegetations on the plateau, alpine grassland mainly composed of steppes and meadows accounts for excess 50% of the gross area and supplies foods and forages for the livings of about 5 million people (Editorial Committee of Vegetation Map China 2007; Bao et al. 2019). Characterized by the alpine climate, vegetation growth is assumed to be restricted by low temperature, and it is predicted that the continuous warming in the future would pose large impacts on grassland on the plateau (Wang et al. 2022; Wang et al. 2023). However, Piao et al. (2017) found that the sensitivity of vegetation growth to air temperature variation in early century decreased since warming appeared more during nongrowing seasons. And it seemed that the warming in dormant season was not profit to the preservation of winter snow, which might influence the vegetation growth by lowering the water supply (Wang et al. 2018). And it seemed that precipitation played a more and more important role in regulating plant growth and phenology for grassland (Sun et al. 2013; Guo et al. 2014; Li et al. 2020a; Shen et al. 2022). However, the impact of different environmental factors may vary across different spatial or temporal scales. e.g., some studies suggested that the plant growth at alpine meadows was more sensitive to temperature variations, while that in drier steppes was more determined by moisture conditions (Liu et al. 2023).

Although some researchers proved that the climate mainly determined the annual variation of alpine grassland coverage on the Qinghai-Tibet Plateau (Huang et al. 2016; Lehnert et al. 2016), anthropogenic activities like grazing and fencing also pose large impacts on grasslands of the plateau (Miehe et al. 2019; Sun et al. 2020). e.g., Pan et al. (2017) reported that the nonclimatic factors like land use changes during 1982-2013 mainly regulated the annual variation of Tibetan Plateau grassland. Miehe et al. (2008) even believed that the most existing *Kobresia pygmaea* grassland on the plateau should be covered by forests without grazing. Recently, Zhao et al. (2022) found that the precipitation exerted more impacts on NDVI (Normalized Difference Vegetation Index) changes than temperature and grazing in the Qomolangma Nature Reserve based on different remote sensing data during the past 19 years (2000–2018). Therefore, whether climate change or anthropogenic activities are more associated with vegetation growth on the plateau is still controversial. A better understanding on grassland changes at different scales may provide important guidance for government policy and grassland management.

The Zhegucuo valley on the Tibetan Plateau is a vital rangeland ecosystem with great importance for water resources and ecological security of the Tibetan Autonomous Region. In 2020, in view of the important ecological value, the Zhegucuo grassland was selected for the first batch of the national grassland and natural park pilot construction list. However, the area of Zhegucuo lake was found to be shrinking under warming climate during past decades (Zhang et al. 2019), which might pose great threats on the grassland, as well as the pastoralists whose livelihoods depend largely on livestock sustained by grasslands and water resources. Previous studies have not distinguished anthropogenic drivers and climate drivers on a local fine geographic scale like Zhegucuo valley, where the respective effects of human activity versus climate on vegetation growth remain unclear. In particular, knowledge related to the contributions arising from anthropogenic factors remains extremely scarce due to the absence of data on the intensity of anthropogenic activities. A thorough understanding of the relative contribution of each driving factor is essential for developing sustainable management capable of coping with consequences of climate change. This work utilizes the most reliable satellite remote sensing products to date to assess the dynamics of grasslands in the Zhegucuo valley from 2000 to 2020. Our aims are to: (1) depict the temporal and spatial patterns of NDVI changes for the Zhegucuo grassland, and (2) reveal the main factors regulating grassland NDVI, and (3) disclose the relative contributions of climate variability and anthropogenic activities to vegetation changes.

2 Research Area and Research Methods

2.1 Overview of the study area

This study area, the Zhegucuo valley (28°28′N – 28°50′N, 91°16′E – 91°50′E), sits in Cuomei County of Shannan city, southern Tibet (Fig. 1). Located on the northern slope of the Himalayas Mountains, the valley possesses an area of 1,279.06 km² which makes up for 30.21% of the area of Cuomei County. The altitude in this region ranges between 4,609 m and 5,902 m. The climate is deeply controlled by the South-Asia monsoon in summer and the westerlies in winter. The meteorological data during last two decades (2000-2020) indicated that the mean annual air temperature and precipitation is -0.7°C and 322.7 mm, respectively. And the temperature in coldest (January) and warmest (July) month is -9.9°C and 8.2°C, respectively. More than 82% of the annual precipitation falls in the growing season (May to September). As Fig. 1 illustrated, the alpine grassland is the main vegetation cover type. Specifically, the distribution area of alpine steppe, meadow, desert and alpine shrub are 666.45 km², 486.92 km², 59.46 km² and 27.89 km² which account for 52.10%, 38.07%, 4.65% and 2.18% of the study area (Editorial Committee of Vegetation Map

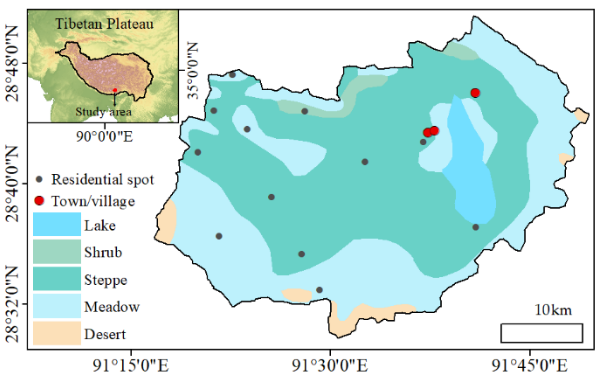

Fig. 1 Location and vegetation types of the Zhegucuo valley on the southern Tibetan Plateau. This map was plotted using ESRI ArcGIS 10.7 desktop.

China 2007), respectively. As one of the most famous scenic spots in Cuomei County, the Zhegucuo lake and its surrounding areas are important pasture for yaks and sheep since ancient times.

2.2 Data processing

Based on the 1:1000,000 vegetation map of China (https://data.tpdc.ac.cn/, accessed on 23 September 2022), we selected the alpine meadow and steppe in the Zhegucuo valley as the research object since these were dominant vegetation types in this area. We applied two remote sensing datasets, one is the SPOT (Systeme Probatoire d'Observation de la Terre) NDVI downloaded from the Resources and Environment Science and Data Center of the Chinese Academy of Sciences (https://www.resdc.cn/, accessed on 7 August 2019), the other is MODIS NDVI (Moderate Resolution Imaging Spectroradiometer) from the NASA (National Aeronautics and Space Administration) website (MOD13A3 datasets, accessed on 24 May 2020). The spatial resolution of NDVI is 1 km × 1 km and the temporal resolution is 1 month, with a time interval of 2000-2018 for SPOT NDVI and 2000–2020 for MODIS NDVI. The data quality of MODIS NDVI was controlled through the quality control layer in MOD13A3. MODIS NDVI and SPOT NDVI, which are highly correlated with each other, have been widely used in studies of vegetation dynamics on the Tibetan Plateau, and their credibility has been demonstrated in previous studies (Liu et al. 2022; Wang et al. 2022). The maximum NDVI during May to September (i.e., the growing season) was used to analyze the temporal trends in this study, since the maximum value reflected the variation of vegetation cover and biomass, as well as the dynamic changes of NPP sensitively (Davis et al. 2017). Though the temporal resolution for MODIS NDVI we applied in this study is 1 month, it is based on 8-days of surface reflectance data using the Maximum Value Composite method to produce a 16-day dataset. Therefore, the maximum NDVI here refers to the highest monthly NDVI values occurring between May and September.

The temperature and precipitation data during 2000–2020 were downloaded from the National Tibetan Plateau Data Center (retrieved on 15 June 2022) and the high-resolution precipitation dataset over the Qinghai-Tibet Plateau from the latest climate reanalysis produced by ECMWF (European Centre for Medium-Range Weather Forecasts.) (Jiang et al. 2021), respectively. Considering that the significant time-lag and -accumulation effects of climatic factors on global vegetation growth (Ding et al. 2020b), the maximum NDVI generally occurs at the peak of the plant growing season (Late July or early August), it is our opinion that the climatic elements in the early growing season (May to July) are the centrepiece of alpine plant growth (Zhao et al. 2019; Li et al. 2020b). We calculated the corresponding GST (Temperature during the early growing season) and GSP (Precipitation during the early growing season) during May to July, with a resolution of 0.03° × 0.03° and 0.01° × 0.01°, respectively. Here, the GST referred to the average temperature, while the GSP referred to the accumulated precipitation during May to July. The data for the number of livestock of Cuomei County is from the Tibet Statistical Yearbook (accessed on 12 February 2020) and the National Tibetan Plateau Data Center. The numbers of different livestock were converted to standard sheep units (Yu et al. 2012). The hydrological analysis tool in the ArcGIS toolbox was used to obtain watershed information based on the Digital Elevation Model (90m, retrieved on 24 August 2022), following the traditional watershed extraction method (Ma et al. 2008). The extracted watershed information was visually assessed by overlaying it on a high-resolution ArcGIS Earth image (World Image), confirming that the extracted watershed information was generally consistent with the ground reality.

2.3 Analysis of interannual change trends in NDVI

We applied univariate linear regression to calculate the trends in the NDVI and meteorological data of the Zhegucuo valley during 2000–2020. A positive slope value suggests that the NDVI is in an increasing trend while a negative one indicates that the NDVI is decreasing, then a slope of zero means that the NDVI shows no change trend and remains steady in every pixel (Stow et al. 2003). The formula is:

$$\theta_{\mathrm{Slope}}=\frac{n\times\sum_{i=1}^{n} i\times \mathrm{NDVI}_i-\sum_{i=1}^{n} i\sum_{i=1}^{n}\mathrm{NDVI}_i}{n\times\sum_{i=1}^{n} i^2-(\sum_{i=1}^{n} i)^2} \quad (1)$$

where θ_{Slope} is acting as proxy for interannual in NDVI, n represents the length of the research period (n=21), and NDVI_i is the NDVI value of the ith year. If $\theta_{\mathrm{Slope}}>0$, the NDVI trend during the 21 years was positively increased; if $\theta_{\mathrm{Slope}}<0$, the trend decreased. In addition, the significance of variation was determined via Student tests to calculate confidence levels.

2.4 Partial correlation analysis between grassland NDVI and climatic factors

The partial correlation analysis was applied to detect the impact of climate variables on grassland NDVI changes. The formula of the partial correlation coefficient as calculated as follows:

$$R_{\mathrm{NDVI\ GST\cdot GSP}}=\frac{R_{\mathrm{NDVI\ GST}}-R_{\mathrm{GST\ GSP}}\times R_{\mathrm{NDVI\ GSP}}}{\sqrt{(1-R^2_{\mathrm{GST\ GSP}})\times(1-R^2_{\mathrm{NDVI\ GSP}})}} \quad (2)$$

$$R_{\mathrm{NDVI\ GSP\cdot GST}}=\frac{R_{\mathrm{NDVI\ GSP}}-R_{\mathrm{GST\ GSP}}\times R_{\mathrm{NDVI\ GST}}}{\sqrt{(1-R^2_{\mathrm{GST\ GSP}})\times(1-R^2_{\mathrm{NDVI\ GST}})}} \quad (3)$$

Here $R_{\mathrm{NDVI\ GST\cdot GSP}}$ represents the partial correlation coefficient of grassland NDVI and GST when GSP is fixed, $R_{\mathrm{NDVI\ GSP\cdot GST}}$ refers to that of NDVI and GSP when GST is fixed. $R_{\mathrm{NDVI\ GST}}$, $R_{\mathrm{NDVI\ GSP}}$ and $R_{\mathrm{GST\ GSP}}$ are the correlation coefficients of grassland NDVI and GST, NDVI and GSP, and GST and GSP, respectively. Excel 2019 and IBM SPSS 19.0 (Statistical Product Service Solutions) were applied for above statistical analysis.

2.5 Residual trend analysis methods

It can be hypothesized that the climate variation determined the change of vegetation growth. Then, the non-climate (anthropogenic activities) induced vegetation changes could thus be identified after removing the climate effects (Evans et al. 2004; Wessels et al. 2007). The RESTREND (residual trend) method, based on the above assertion, can be used to detect the relative impacts of climate variability versus anthropogenic activities. After removing the climate influence, the human-induced vegetation change could thus be identified. The trends in NDVI residuals ($\mathrm{NDVI_H}$), the deviation between the observed ($\mathrm{NDVI_A}$) and the predicted value ($\mathrm{NDVI_P}$) were calculated. We first set up a statistical model by regressing $\mathrm{NDVI_A}$ against climatic factors of GSP (P-value of 0.001), and then applied this model to compute the $\mathrm{NDVI_P}$ of GSP for each pixel (Jin et al. 2020; Zhao et al. 2022; Li et al. 2023). A positive trend in $\mathrm{SlopeNDVI_A}$ is associated with better vegetation growth, while a negative trend in $\mathrm{SlopeNDVI_A}$ is associated with worse vegetation growth. Positive trends in the residuals indicate that vegetation restoration mainly caused by human influence, such as conservation or restoration projects, has occurred, whereas negative trends indicate human-induced vegetation degradation. Table 1 depicted the relative impacts of climate variability ($\mathrm{SlopeNDVI_P}$) versus human activities ($\mathrm{SlopeNDVI_H}$)

Table 1 Assessment methodology of climate variation and anthropogenic activities on grassland changes under six scenarios. Different symbols denote trend: ● positive trend; ○negative trend.

Scenario	Slope $NDVI_A$	Slope $NDVI_P$	Slope $NDVI_H$	Relative role of climate change (%)	Relative role of human activities (%)	Description
1	●	○	●	0	100	HI: HA contributes to grassland $NDVI_A$ increase
2	●	●	○	100	0	PI: CC contributes to grassland $NDVI_A$ increase
3	●	●	●	$\frac{\lvert SlopeNDVI_P\rvert}{\lvert SlopeNDVI_A\rvert}$	$\frac{\lvert SlopeNDVI_H\rvert}{\lvert SlopeNDVI_A\rvert}$	HPI: Both CC and HA contribute to $NDVI_A$ increase
4	○	●	○	0	100	HD: HA contributes to grassland $NDVI_A$ decrease
5	○	○	●	100	0	PD: CC contributes to grassland $NDVI_A$ decrease
6	○	○	○	$\frac{\lvert SlopeNDVI_P\rvert}{\lvert SlopeNDVI_A\rvert}$	$\frac{\lvert SlopeNDVI_H\rvert}{\lvert SlopeNDVI_A\rvert}$	HPD: Both CC and HA contribute to $NDVI_A$ decrease

* CC and HA denote climate change and human activities respectively.

on grassland NDVI changes ($SlopeNDVI_A$) in six scenarios (Zhang et al. 2018; Jin et al. 2020; Liu et al. (2019). When $SlopeNDVI_A$ has a positive trend, and $SlopeNDVI_P$ and $SlopeNDVI_H$ have negative and positive trends, respectively, it means that the change in $NDVI_A$ is not related to the change in $NDVI_P$, and the contribution of $NDVI_H$ to $NDVI_A$ is 100%, i.e., anthropogenic activities have caused an increase in NDVI in the grassland in the study area (Scenario 1). When $SlopeNDVI_A$ has a positive trend, and $SlopeNDVI_P$ and $SlopeNDVI_H$ have positive and negative trends, respectively, it means that the change of $NDVI_A$ is not related to the change of $NDVI_H$, and $NDVI_P$ contributes 100% to $NDVI_A$, i.e., climate change causes the increase of NDVI in the grassland of the study area (Scenario 2). The remaining four scenarios are detailed in Table 1, and more details about the RESTREND analysis can be found in Li et al. (2012) and Zhang et al. (2018).

3 Results and Analysis

3.1 Spatiotemporal Variations in NDVI

During the last two decades, the grassland NDVI from MODIS and SPOT data sources in Zhegucuo valley did not reflect a significant temporal change (Fig. 2, MODIS, R^2=0.0002, P>0.05; SPOT, R^2=0.14, P>0.05). Both MODIS and SPOT NDVI were significantly correlated with each other (Fig. 2, inserted box, R^2=0.47, P<0.01). The mean values of MODIS NDVI and SPOT NDVI were 0.36 and 0.33, respectively. The minimum values of both MODIS and

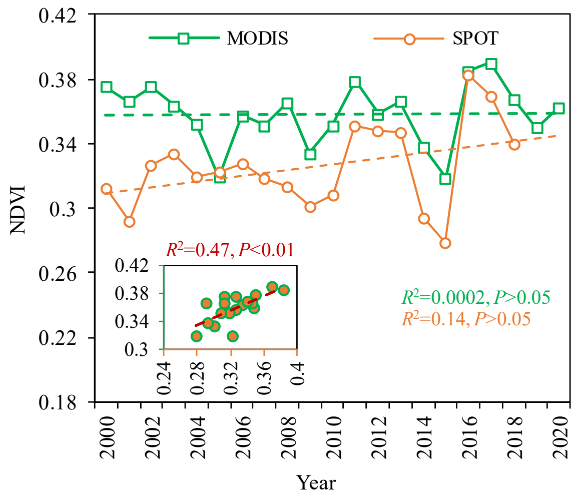

Fig. 2 Interannual variation in SPOT NDVI and MODIS NDVI and their relationships (inserted box) in the Zhegucuo valley during 2000–2020.

SPOT NDVI occurred in 2015, but their maximum values occurred in 2017 and 2016, respectively. In view of the spatial distribution, Appendix 1a additionally revealed that 31.51% of the 1 km×1 km raster exhibited a significant correlation between MODIS and SPOT NDVI, and the spatial and temporal patterns of the two NDVI were similar (Appendix 1b). Those pixels illustrating a decreasing trend were mainly distributed around Zhegucuo lake (in east) and those with an increasing trend were mainly distributed in the west (Fig. 3).

The proportion of raster showing an increasing and decreasing trend in grassland MODIS NDVI during 2000-2020 was 48.53% and 51.47%, respectively. Among the raster showing declining trend,

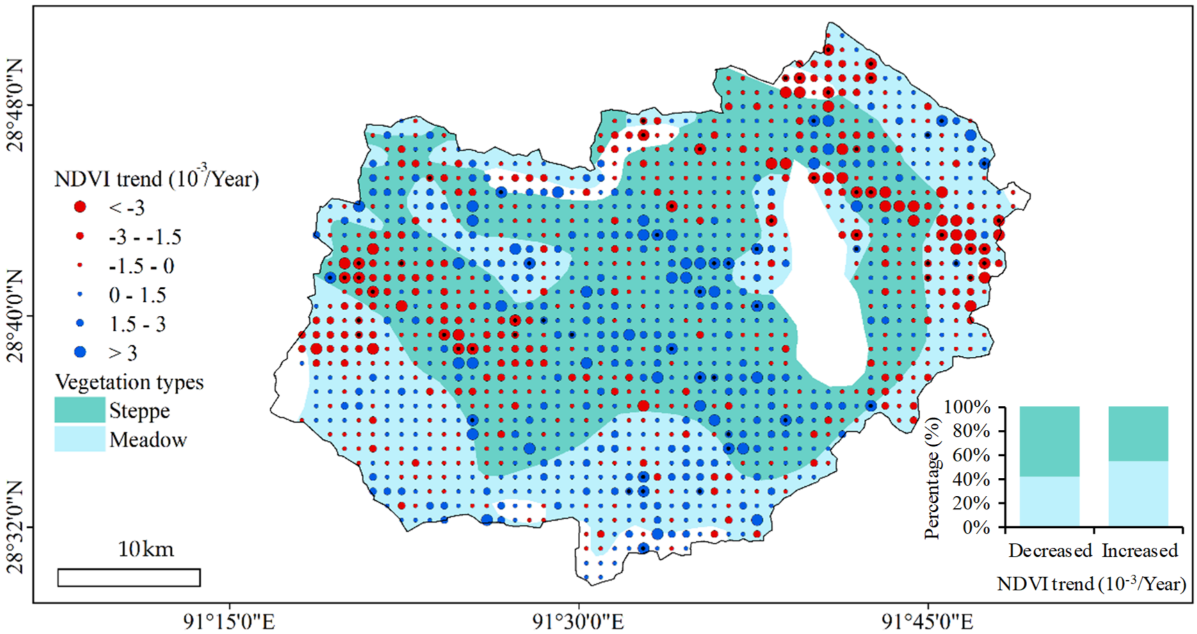

Fig. 3 NDVI trends of different vegetation types during 2000-2020. Black dots denote significant level at $P < 0.05$. The above map was created by ArcGIS 10.7 desktop.

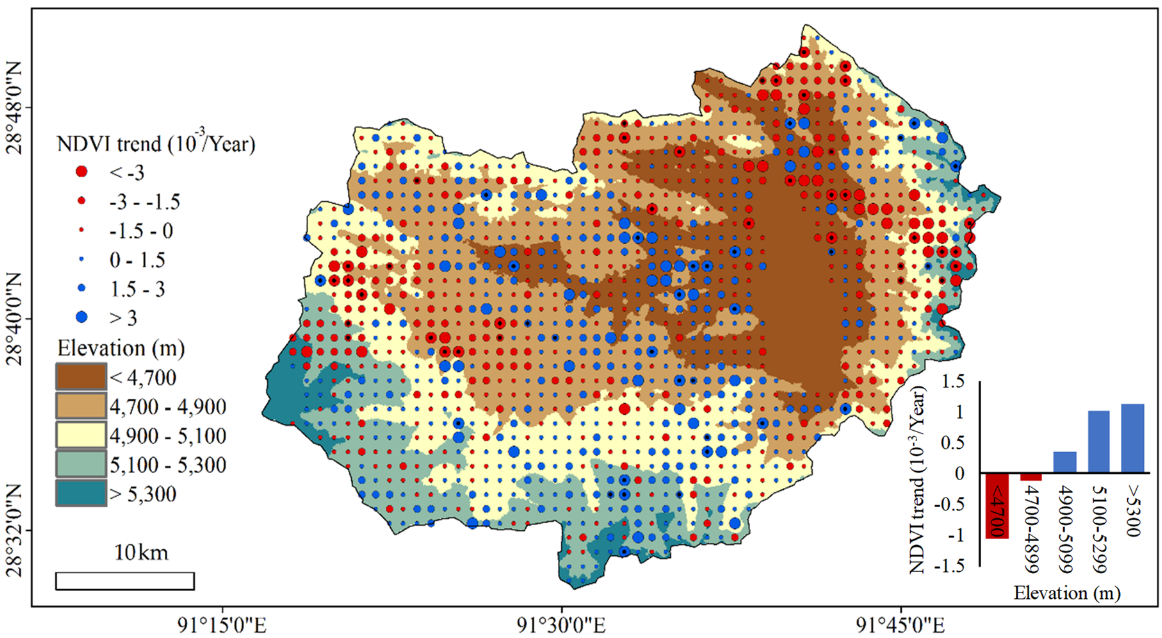

Fig. 4 Altitudinal variations in NDVI during 2000-2020. Black dots denote significant level at $P < 0.05$. The above map was created by ArcGIS 10.7 desktop.

the proportion of MODIS NDVI change rates of <-0.003/year, -0.003 – -0.0015/year, and -0.0015 – 0/year were 4.48%, 13.84%, and 30.21%, respectively, while the proportion of MODIS NDVI increase rates of >0.003/year, 0.0015 – 0.003/year, and 0 – 0.0015/year were 4.72%, 15.15%, and 31.60%, respectively (Fig. 3).

In terms of different vegetation types, there were 61.24% and 31.38% of the raster depicting decreasing MODIS NDVI trends for alpine steppe and alpine meadow, respectively, i.e., the decreasing MODIS NDVI trends mainly happened in alpine steppe rather than meadow (Fig. 3). Similarly, the decreasing MODIS NDVI trends mainly occurred in areas below 4,900 m, where alpine steppe dominated. On the opposite, the increasing MODIS NDVI trends generally

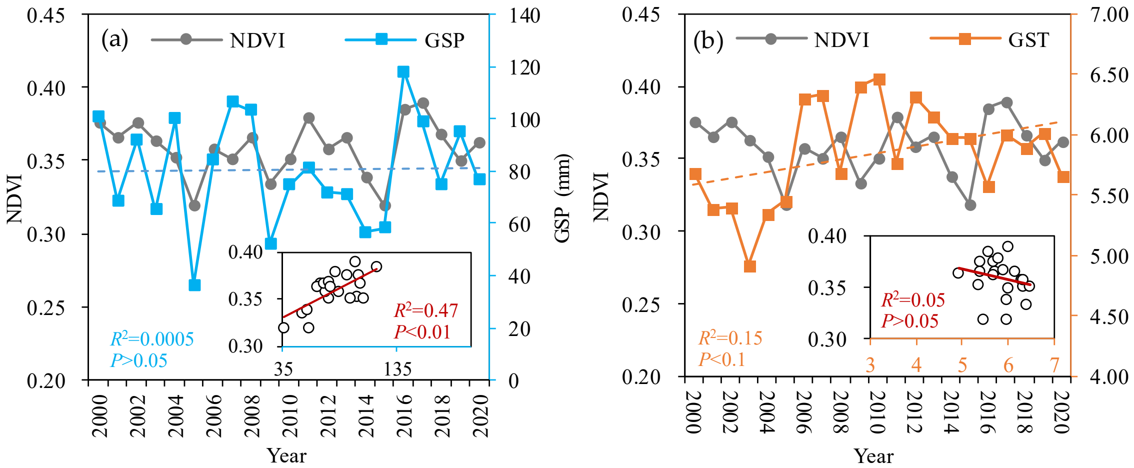

Fig. 5 Temporal variations of climatic factors of (a) GSP (Precipitation during the early growing season) and (b) GST (Temperature during the early growing season) and their relationships with MODIS NDVI in the Zhegucuo valley during 2000–2020.

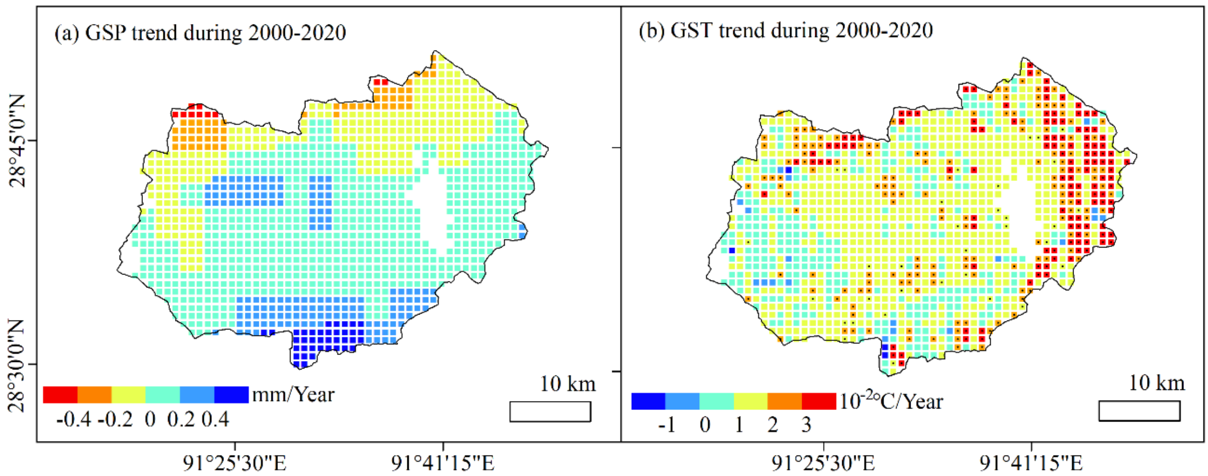

Fig. 6 Spatial variations of (a) GSP and (b) GST in the Zhegucuo valley during 2000–2020. Black dots denote significant level at P < 0.05. The above map was drawn using ArcGIS 10.7 desktop.

happened in areas above 4,900 m, where alpine meadow dominated (Fig. 4).

3.2 Variations in temperature and precipitation and their effects on NDVI

During 2000-2020, both GSP (Fig. 5a, R^2=0.0005, P>0.05) and GST (Fig. 5b, R^2=0.15, 0.05<P <0.10) did not show significant temporal changes. However, the annual variation in GSP resembled that of MODIS NDVI, e.g., the minimum GSP corresponded to the lowest MODIS NDVI in 2005, while the maximum GSP corresponded to the second maximum NDVI value in 2016. Thus, there showed a significantly positive relationship between GSP and MODIS NDVI (Fig. 5a, inserted box, R^2=0.47, P<0.01). Whereas GST was not correlated with MODIS NDVI (Fig. 5b, inserted box, R^2=0.05, P>0.05). In view of the spatial distribution, GSP (Fig. 6a) and GST (Fig. 6b) tended to increase in the southern and eastern part, respectively.

At pixel level, the partial correlation analysis reflected that GSP usually exerted positive effects on NDVI, while GST showed negative impacts. For GSP, there were 37.79% and 31.67% of the total pixels reflecting positive relationships with MODIS and SPOT NDVI, respectively (Fig. 7a and Appendix 2a). For GST, 11.32% and 9.20% of the total pixels reflected significantly negative correlation to MODIS and SPOT NDVI, respectively (Fig. 7b and Appendix 2b). In view of the spatial distribution, the areas affected by GSP mainly sat in the southern part, while those affected by GST stood in the eastern part, mainly around the Zhegucuo lake where most population in Cuomei County settled down.

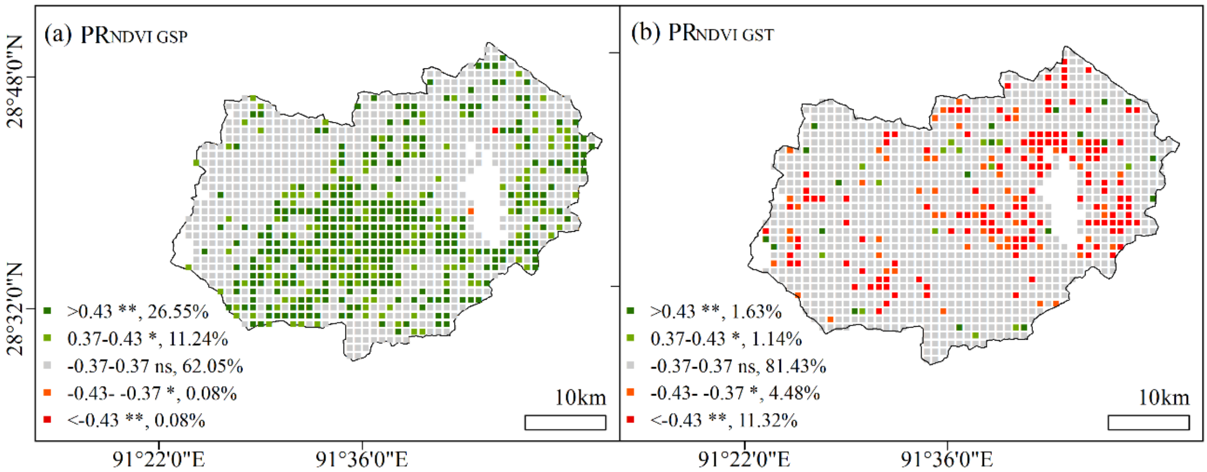

Fig. 7 Spatial heterogeneity patterns of the partial correlation coefficients between grassland NDVI and climatic elements of (a) GSP and (b) GST. Several colors denote the classes of partial correlation coefficients. Different marks represent significant levels: ** $P < 0.05$, * $0.05 < P < 0.10$, ns, not significant. The above map was created by ArcGIS 10.7 desktop.

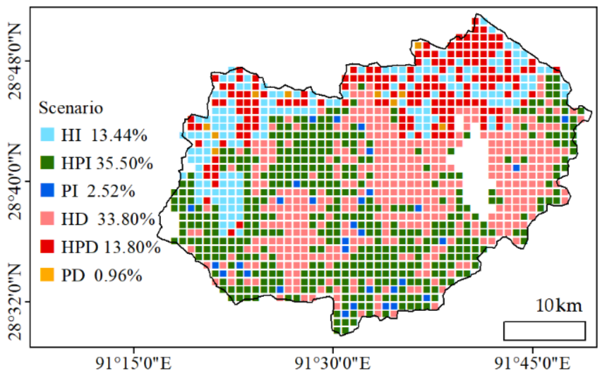

Fig. 8 Relative influence of climatic variation and human activities on grassland NDVI changes in the Zhegucuo valley during 2000–2020. HI, human activities caused an increase in NDVI; PI, climate variation caused an increase in NDVI; HPI, human activity and climate variation caused an increase in NDVI; HD, human activities caused a decrease in NDVI; PD, climate variation caused a decrease in NDVI; HPD, NDVI decrease induced by both human activities and climate variation. The above map was created by ArcGIS 10.7 desktop.

3.3 Relative effects of climate and anthropogenic activities

Based on the 6 possible scenarios of climate change and human activities, the relative roles of them were shown in Fig. 8. The RESTREND analysis reflected that the research area showing rising MODIS NDVI accounted for 51.46% of the whole area, in which 2.52% was caused by climate variation (Scenario 2), 13.44% by anthropogenic activities (Scenario 1), and 35.50% by both climate variation and human activities (Scenario 3). The area reflecting decreasing MODIS NDVI accounted for less than half of the total area, in which 33.80% was caused by anthropogenic activities (Scenario 4), 0.96% by climate change (Scenario 5), and 13.80% by both climate variation and anthropogenic activities (Scenario 6). The reasons for MODIS NDVI decrease or increase showed apparent dissimilarities. Human activities had a great impact on the decline of MODIS NDVI, while the combined climate change and human activities could promote the recovery of MODIS NDVI. It is worth noting that grasslands favorably affected by anthropogenic activities were mainly distributed around the Zhegucuo lake in the eastern part, where the MODIS NDVI tended to decrease. The increased area of MODIS NDVI caused by human activities was mainly distributed in the north of the study area, and those induced by both climate change and human activities was mainly allocated in the middle and southwest of the study area.

4 Discussion

4.1 Precipitation or temperature mediated the annual variation of NDVI

During 2000-2020, the temporal variation of GSP resembled that of NDVI in this study area, and explained near half of the changes in MODIS NDVI. However, GST here presented less explanation. Also, partial correlation analysis at pixel level indicated that the variation of GSP explained more of the variation of

MODIS NDVI than GST (26.24% vs. 11.32%). Therefore, compared with temperature, it seemed that the precipitation exerted larger impacts on the temporal changes of MODIS NDVI, in accordance with previous reports on the Qinghai-Tibet Plateau (Han et al. 2023; Zhang et al. 2015; Sun et al. 2016; He et al. 2019). Li et al. (2020) further emphasized that the time and magnitude of precipitation is more important than temperature itself in determining vegetation growth, and pointed out that the rainy season onset and its interactions with precipitation and temperature mainly explained the spatial-temporal variability of spring vegetation green-up on the plateau. From the respect of vegetation distribution pattern in the Zhegucuo valley, the area of alpine steppe accounts for more than half of the whole area (52.10%), while that of alpine meadow, mainly distributed in high elevations in the surrounding mountains, makes up for only about one thirds (38.07%), suggesting the climate in this area is relative drier compared with that on the eastern Qinghai-Tibet Plateau where the humid alpine meadow dominates. Accordingly, we could ascertain that it might be precipitation rather than temperature mediated the temporal changes in MODIS NDVI in this area where the drier ecosystem of alpine steppe dominates.

It is worth noting that the annual fluctuation of GSP rather than its temporal trend mainly determined the MODIS NDVI changes, which is in accordance with Zhang et al. (2013) who reported that the declining MODIS NDVI in the Kosi River Basin in the southern slope of the central Himalayas was associated with a drop in precipitation. Another study carried out in the Qomolangma Nature Reserve and nearby areas also supported this assertion (Zhao et al. 2022). Therefore, we need to put an eye on the influence of extreme climate incidents like extreme rainfall years rather than a simple linear variation trend (Liu et al. 2019)

Although the precipitation seemed to play a more pivotal role than temperature, we could see that the temperature tended to increase marginally for the whole valley, and statistically significant in the eastern part. Compared with this, the precipitation did not vary during the last 21 years, neither at the whole valley scale nor at the pixel level. This indicate that the climate here tends to be warmer and drier rather than being warmer and wetter as reported for most area of the Tibetan Plateau. Under scenarios of warmer and drier climate, the strengthened evapotranspiration would assume to occur, which might be disadvantageous to the growth of grassland, especially for the dry steppe.

The SPOT sensors have changed a little bit by the replacement of the VGT1 by the VGT2 in 2003, involving a change in spectral response functions of channels 1 and 2 (Fensholt et al. 2009), while the MODIS remote sensor have narrower red and near infrared bands, making them more sensitive to changes in vegetation chlorophyll (Zhu et al. 2019), enabling the more accurate basis for detecting changes in vegetation dynamics. Furthermore, the time series for MODIS NDVI is longer than that of SPOT NDVI (21 versus 19 year). Therefore, we mainly focused on analyzing the characteristics of MODIS NDVI and the relative impacts of climate change and anthropogenic activities on it in this paper.

4.2 Impact of anthropogenic activities on NDVI changes

Large scale studies suggested that the climate factors played a more pivotal role than anthropogenic activities in mediating vegetation changes over the Tibetan Plateau (Huang et al. 2016; Lehnert et al. 2016; Naeem et al. 2020; Yu et al. 2021). However, the impact factors may vary on different temporal and/or spatial scales (Zhu et al. 2022; Zhang et al. 2022). In our study, it seemed the main impact factor on MODIS NDVI changes shifted to anthropogenic activities during the last 21 years on a valley scale. The results of RESTREND analysis indicated that anthropogenic activities and climate change, alone or in combination, are responsible for 48.56% of the decline in MODIS NDVI of grasslands in the study area, with anthropogenic activities alone contributing to 33.80% of the decline in NDVI. That is, the vegetation degradation in this region is mainly due to anthropogenic activities, consistent with Zhu et al. (2022) who found that the anthropogenic activities caused 45.7% vegetation degradation during 2000-2019 on the whole Tibetan Plateau. From respect of geographic distribution, degradation mainly occurred in the center-eastern part around the Zhegu Lake. This is because the main residential settlements, Zhegu Town, Zhegu Village and Zongzong Village, which possess most of the population in this valley, sit near the Zhegu Lake (Fig. 1). According to the fifth and seventh census data, the resident population of Cuomei County was 13,500 and 12,100 in 2000 and 2018 (https://www.hongheiku.com/), respectively. The population has not increased significantly over the last

20 years. Although the Gross Domestic Product of Cuomei County has been increasing year by year, the impact on vegetation has been indirect. Cuomei County is situated in the high-altitude pastoral area of the Tibetan Plateau. The county has a high proportion of pastoral income, and grazing activities are the primary source of negative impact on grasslands. And grazing reflected by the number of livestock, as one of the most important anthropogenic activities, tended to decrease during past decades (Fig. 9) and is thus assumed to pose deep effects on the variation of MODIS NDVI here.

Apart from negative impacts, anthropogenic activities may also exert positive effects on vegetation growth (Zhang et al. 2019; Yan et al. 2015; Hao and He 2019). In this area, anthropogenic activities alone, and together with climate change contributed 13.44% and 35.5% of the increase in MODIS NDVI, respectively. As an important way of vegetation recovery, fencing is widely applied throughout the whole plateau (Sun et al. 2021). Part of the fencing area where grazing is excluded can be found to be distributed in the northeast part of the valley, partly corresponding to the anthropogenic-induced increases in MODIS NDVI.

Anthropogenic activities like land use change may affect the distribution of water resources, and even decrease the area of Zhegucuo lake by artificial reclamation or cross-lake bridge construction, which might alter water cycling processes and ultimately impact the feedback between water vapor and vegetation growth. Therefore, the impact of anthropogenic activities on grassland needs to be accessed and fully considered in future sustainable management.

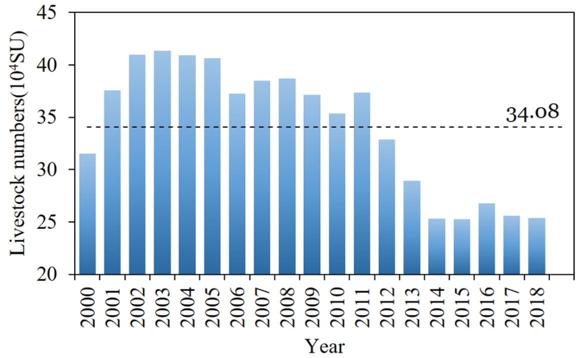

Fig. 9 Interannual variations in livestock numbers of Cuomei County during 2000-2020. SU denotes standard sheep units.

5 Conclusion

In summary, grasslands in the Zhegucuo valley of the southern Tibetan Plateau did not show a greening trend during 2000-2020. With respect to climatic factors, it was precipitation rather than temperature that mediated the annual variation of grassland NDVI. In view of the spatial distribution, the areas affected by precipitation mainly sat in the southern part, while those affected by temperature stood in the eastern part, mainly around the Zhegucuo lake where most population in Cuomei County settled down. Therefore, the grasslands favorably affected by anthropogenic activities were mainly distributed around the Zhegucuo lake where the grassland NDVI tended to decrease. Future studies should pay more attention on climate extremes like precipitation extremes rather than the simple temporal trends. And the influence of human activities on grassland needs to be fully accessed in future sustainable management.

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Author Contributions

Conceptualization: ZHANG Lin, ZHANG Huifang; Methodology: WANG Heng-ying, ZHAO Wanglin; Formal analysis and investigation: ZHANG Lin, ZHANG Huifang; Writing - original draft preparation: ZHAO Wanglin, ZHANG Lin; Writing - review and editing: ZHANG Lin, WANG Hengying; Funding acquisition: ZHANG Huifang, ZHANG Lin; Resources: ZHAO Wanglin, ZHANG Lin; Supervision: WANG Hengying, ZHANG Lin; Visualization: ZHAO Wanglin. All authors have read and agreed to the published version of the manuscript.

Ethics Declaration

Availability of Data/Materials: The datasets used in this study can be downloaded from the websites listed in the text.

Conflict of Interest: The authors declare no conflict of interest.

Electronic Supplementary Material:

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