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**Spatial heterogeneity of changes in vegetation growth and their driving forces
based on satellite observations of the Yarlung Zangbo River Basin in the Tibetan
Plateau**

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Abstract: Changes in vegetation growth may influence the availability of water resources. Located on the Tibetan Plateau, the Yarlung Zangbo River Basin (YZRB) is a major freshwater source for Tibet, China and downstream South Asian countries, with high spatial heterogeneity in altitude and climate from the upstream to downstream regions. In this study, we combined satellite-based gridded datasets of the normalized difference vegetation index (NDVI), topography, precipitation, and temperature to investigate how vegetation growth has changed in the YZRB over recent decades (1982–2010), and to determine their driving mechanisms. Although a statistically significant trend in growing season NDVI was not detected at the basin scale, at the pixel scale 16.8% and 5.3% of the area of the YZRB was found to exhibit increasing and decreasing trends, respectively. The greatest increases occurred in the Nyang subbasin. Variations of NDVI values along elevation, precipitation, and temperature gradients revealed the greatest variation over the middle ranges of the three variables. Partial correlation analyses indicate that in both arid and semi-arid regions of the YZRB precipitation is positively correlated with NDVI. The relationship between NDVI and temperature varies with aridity, reflecting different effects of snow-melting processes on vegetation growth. Temperature positively correlates with NDVI in the arid region. In addition, a negative correlation between NDVI and temperature is detected in the semi-arid region. This is the first comprehensive study to explore climate–vegetation–hydrology relationships in the YZRB at a spatial resolution finer than those derived from sparse in-situ

meteorological stations or low resolution global climate datasets. Our results are valuable for understanding ecohydrological processes in both arid and semi-arid regions of this internationally important river basin.

Keywords: Yarlung Zangbo River Basin; Vegetation Changes; Normalized Difference Vegetation Index; Elevation; Precipitation; Temperature

1 Introduction

As a major carbon sink on Earth, the land has absorbed 24.1% of CO₂ from anthropogenic emissions (Le Quéré et al., 2018). Under global climate change, terrestrial ecosystems in many regions around the world have been influenced by changes in atmospheric CO₂ concentration and meteorological factors (Piao et al., 2006; Ukkola et al., 2016). Given its important roles in regulating both the terrestrial water and carbon cycles, vegetation has been considered as a natural link between the soil, atmosphere, and water (Arora, 2002). Recent studies have indicated that climate change may have significant impacts on the role of vegetation as a carbon sink, and consequently on hydrological processes (Li et al., 2016; Piao et al., 2011). Furthermore, changes in vegetation productivity could alter biophysical factors and energy transfer to the atmosphere, which may lead to effects on local to regional climates (Anderson et al., 2011; Jackson et al., 2008).

Analyses of changes in vegetation growth conditions and their correlations with changing environments have been the subject of considerable research during the past several decades. Typically, to monitor vegetation growth from satellites, the normalized difference vegetation index (NDVI) is used. This index is the ratio of the difference versus sum of near-infrared and red reflectance derived from remote sensing observations. The NDVI is considered to be a proxy for terrestrial vegetation growth (Sun et al., 2015; Zhang et al., 2013), because there is a close relationship between the NDVI and photosynthetically active radiation absorbed by

photosynthesizing tissues (Myneni et al., 1997). Given their broad spatial and temporal coverage, remotely sensed Global Inventory Monitoring and Modeling System (GIMMS) NDVI data have been widely employed to analyze vegetation trends and processes on continental and regional scales (e.g., Piao et al., 2011; Fensholt et al., 2012; Ukkola et al., 2016). The dataset is available from the early 1980s, which makes it possible to trace changes in vegetation over the past few decades. Basins are one of the most important spatial scales for fresh water resource management, as a basin defines all areas that drain to a given basin outlet (Vicuna et al., 2010). Examination of how vegetation changes are related to various driving factors is essential to a thorough understanding of ecohydrological processes within a basin. It also improves our knowledge of water resource dynamics (Leakey et al., 2009), especially in arid or semi-arid basins, where competition for freshwater resources between humans and nature is more severe.

Located on the Tibetan Plateau (TP), the Yarlung Zangbo River Basin (YZRB) provides major freshwater resources for Tibet, China and downstream South Asian countries, which gives it global importance. It is the highest basin in the world, with a large difference in elevation between its source and downstream areas. The climate transitions from cold and dry conditions in the upstream region to warm and humid conditions in the downstream region, leading to a high diversity of vegetation within the basin (Guo et al., 2018). Li et al. (2013) and Liu et al. (2014) demonstrated that both climate changes and land-use/cover influence runoff in the YZRB. Therefore,

determining how vegetation changes and what drives these changes will lead to a better understanding of the water cycle within the basin. Previous studies have indicated that rising temperatures have contributed to rising vegetation productivity in Eurasia and on the TP over the past decades (Li et al., 2016; Piao et al., 2011; Zhang et al., 2013). Nevertheless, in the YZRB, the spatial distribution of the linkage between climate change and vegetation growth has not been adequately quantified within the basin, because previous studies mostly used limited data from sparsely distributed meteorological stations or global datasets with coarse resolutions (e.g., Xu et al., 2013; Li et al., 2015; Han et al., 2018).

To further our understanding of climate–vegetation–hydrology relationships in the YZRB, the objective of this study was to explore how vegetation growth has changed in the YZRB and which climatic factors have driven vegetation growth over recent decades. Such information will improve our knowledge of ecohydrological processes under different elevation and climate conditions in this unique and important basin, especially within arid to semi-arid high-altitude continental plateau regions. The GIMMS NDVI dataset was used to evaluate vegetation growth. Unlike previous studies, the meteorological data used herein were derived from a satellite-based gridded dataset with a 5-km spatial resolution. This dataset enabled us to explore the spatial heterogeneity of the relationships between vegetation growth and various meteorological factors in the YZRB. In this paper, we first investigate the spatial distribution and inter-annual trends of growing season GIMMS NDVI values

for 1982–2010. We then explore how growing season NDVI values change along gradients of elevation, temperature, and precipitation. Finally, spatial distributions of the relationships between the NDVI and meteorological factors (temperature and precipitation) are analyzed and discussed.

2 Material and methods

2.1 Study area

The YZRB, stretching across the southern edge of the TP, is approximately 2,057 km long, with a drainage area of $2.4 \times 10^5 \text{ km}^2$. It originates from the Jiemayangzong Glacier in south-central Tibet and is one of the highest major river basins in the world. It initially flows from west to east but bends towards the northeast near Milin Town. It then turns south and passes through the Yarlung Zangbo Grand Canyon, before flowing to India. Fig. 1 shows the location of the YZRB and its topography. From the western upstream area to the eastern canyon area, the elevation decreases dramatically from about 7,000 m to 150 m, with an average elevation of roughly 4,500 m above sea level. The river has six major tributaries from its upper- to lower-reaches regions (Fig. 2): the Dogxung Zangbo, Nyangqu, Lhasa, Nyang, Yigong Zangbo, and Purlung Zangbo Rivers, traversing Ngari, Shigatse, Lhasa, Nagqu, Nyingchi, Qamdo, and Shannan prefectures of Tibet, China (Fig. 3).

Fig. 1 Location of the Yarlung Zangbo River Basin in China and its topography.

Fig. 2 Mainstream and major tributaries of the Yarlung Zangbo River.

Fig.3 Prefectures of Tibet, China traversed by the Yarlung Zangbo River.

Fig.4 Land-cover map of the Yarlung Zangbo River Basin derived from moderate resolution imaging spectroradiometer data for 2010.

The YZRB is connected to the Indian Ocean water system and exhibits significant variations in climate and land-cover from the upstream to downstream regions, because of the considerable topographical differences along its length. Generally, the climate of the YZRB is characterized by intense solar radiation, low air temperature, and high daily variations but low annual variations in temperature, with a clear division between the dry (from October to April) and wet (from May to September) seasons (Li et al., 2013). The land-cover map for 2010 derived from moderate resolution imaging spectroradiometer data (Fig. 4) shows an obvious change in vegetation types across the YZRB, related to topography. The upstream region is located within a frigid zone, with a mean annual precipitation of less than 300 mm; it is mainly covered by alpine meadows. The midstream region has a continental climate, with annual precipitation of 300 – 600 mm; it is dominated by alpine grassland. The downstream region has a warm and humid subtropical climate, with a maximum annual precipitation of more than 2,000 mm; it is mainly covered by coniferous and broadleaf forest. The basin is a reference area for studying both the change and

vulnerability of ecosystems in response to climate change (Tan et al., 2010; Zeng et al., 2018).

2.2 Data sources and processing

The NDVI values used in this study were obtained from the GIMMS biweekly NDVI dataset, generated from NOAA's advanced very high resolution radiometer, with spatial resolution of 8 km from 1981 to 2015 (<https://nex.nasa.gov/nex/projects/1349/>).

The monthly NDVI data used in this study were generated by applying the maximum value composite method (Holben, 1986) to the two images for each month to reduce noise, which retained the highest value for each pixel. Herein, the average growing season NDVI was defined as the average monthly NDVI value from April to October. The pixels with growing season NDVI values of less than 0.1 were classified as bare ground (Piao et al., 2011).

The gridded precipitation and temperature dataset used in this study was provided by the Land-Atmosphere Interaction Research Group of Sun Yat-sen University, China. The dataset covers 1958 to 2010; it was produced by fusing gauge observations and existing gridded data, including remote sensing products and reanalysis data, with a spatial resolution of 5 km and a temporal resolution 3 h. The details of the dataset are available at: <http://globalchange.bnu.edu.cn/home>. In the YZRB, the high average and large variations of elevation produce high levels of spatial heterogeneity in temperature and precipitation. However, the ground meteorological monitoring network is sparse, which makes it difficult to capture these

complex spatial variations in temperature and precipitation. In this case, the fused gridded data, which provide both the accuracy of ground measurements and the spatial density to ensure reasonable descriptions of this spatial heterogeneity, were essential to evaluating the influence of climate change on vegetation growth in this remote basin.

Considering the availability of NDVI and meteorological data, analyses in this study were carried out for the period from 1982 to 2010. The accuracy of the gridded climate dataset in the YZRB has been verified by Gao et al. (2015) and Fan et al. (2018). To match the spatial and temporal resolutions of the NDVI dataset, we first calculated monthly precipitation and temperature for each grid by adding the 3-hourly precipitation values and averaging the 3-hourly temperature values over one month, respectively. Monthly precipitation and temperature data for each grid were resampled to the same 8-km spatial resolution as the NDVI data using a linear interpolation method. This process yielded 3,290 pixels of NDVI and climate data within the basin, which allowed us to explore the spatial heterogeneity of vegetation growth and its relationship with climate in the YZRB. In each grid, the annual growing season precipitation was calculated by summing monthly precipitation from April to October for each year. The annual average growing season temperature was the average of monthly temperature from April to October for each year.

The relationship between the NDVI and topography in the YZRB was also explored in this study. The digital elevation model (DEM) used in this study was

derived from the NASA Shuttle Radar Topographic Mission (SRTM) dataset (<http://srtm.csi.cgiar.org>), with a 90-m spatial resolution. To make it consistent with the spatial resolution of the NDVI data, the SRTM DEM was resampled to 8-km spatial resolution to investigate the relationship between the NDVI and elevation.

2.3 Methods

To identify trends in NDVI-based greening and climate factors (precipitation and temperature) during the study period (1982–2010), the Mann-Kendall test (Mann, 1945; Kendall, 1975) was employed. For time series data $X = \{x_1, x_2, \dots, x_n\}$, the test statistic S is computed as

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^n \text{sgn}(x_j - x_i) \quad (1)$$

where

$$\text{sgn}(x_j - x_i) = \begin{cases} 1, & x_i < x_j \\ 0, & x_i = x_j \\ -1, & x_i > x_j \end{cases} \quad (2)$$

Assuming these data are independent and identically distributed, the mean and variance of S are given by

$$E(S) = 0 \quad (3)$$

$$\text{VAR}(S) = n(n-1)(2n-5)/18 \quad (4)$$

Considering the existence of tied ranks (equal observations) in the data, the variance of S can be updated to

$$\text{VAR}(S) = [n(n-1)(2n-5) - \sum_{i=1}^m t_i(t_i-1)(2t_i+5)]/18 \quad (5)$$

where m is the number of tied groups, and t_i is the number of data in the i th tied group.

For a sample size > 10 , the standardized normal statistic z is estimated as

$$Z = \begin{cases} \frac{S - 1}{\sqrt{VAR(S)}}, & S > 0 \\ 0, & S = 0 \\ \frac{S + 1}{\sqrt{VAR(S)}}, & S < 0 \end{cases} \quad (6)$$

A comparison between z and the standard normal variate at the desired significance level α , allows the significance of the trend to be determined. In this study, a significance level of 5% was selected, indicating that when $|Z| > 1.96$, the null hypothesis of no trend would be rejected.

For those pixels in which the trend in index values is significant ($P < 0.05$), the magnitude of change per year is computed using Sen's slope estimator (Sen, 1968). The true slope (change per unit time) is calculated as

$$\theta = \text{Median} \left(\frac{x_j - x_i}{j - i} \right), i < j \quad (7)$$

To examine how vegetation changes along gradients of topography, precipitation and temperature, the boxplot method was applied. The multi-year average growing season NDVI for 1982–2010 in each grid was plotted against the corresponding elevation in each grid, grouped in 500 m intervals of elevations. Likewise the multi-year average growing season NDVI values for 1982–2010 were plotted against multi-year average growing season precipitation and temperature values, respectively. The precipitation and temperature data were grouped based on 50 mm and 2.5° C intervals.

To explore the relationships between NDVI values and climate factors, partial

correlation analysis (Kenett et al., 2010; Fu et al., 2014) was used. This method is a powerful tool to investigate the real correlation coefficients between pairs of variables in x and y space, while controlling the variables in z . The partial correlation coefficient is defined, as follows:

$$r_{xy,z} = \frac{r_{xy} - r_{xz}r_{yz}}{\sqrt{(1-r_{xz}^2)(1-r_{yz}^2)}} \quad (8)$$

where $r_{xy,z}$ is the partial correlation coefficient between variables x and y , while controlling for variables in z ; and r_{xy} , r_{xz} , and r_{yz} represent the Pearson correlation coefficients between x and y , x and z , as well as y and z , respectively. To explore the independent contributions of precipitation and temperature to NDVI changes, we first calculated the correlation between the NDVI and precipitation, removing the effect of temperature using partial correlation analysis. Next, the correlation between NDVI and temperature values was computed, while the effect of precipitation was controlled in a similar manner.

3 Results and discussion

3.1 Spatial distributions and trends of the normalized difference vegetation index, temperature, and precipitation

The inter-annual variations of the growing season NDVI, precipitation and temperature at the basin scale for the period of 1982–2010 are shown in Fig. 5. The NDVI and precipitation values showed only a statistically insignificant increase, whereas the basin-averaged growing season temperature increased significantly ($R^2 = 0.576$, $P < 0.00001$) from 4.1°C in 1982 to 6.2°C in 2010, with a total increase of

2.1°C over three decades. This finding is in accordance with previous studies, in which statistically significant positive trends of average growing season temperature were observed over Eurasia (Piao et al., 2011; Tao et al., 2015) and non-significant increasing trends in annual precipitation were observed in the YZRB (You et al., 2007; Tong et al., 2014).

Fig. 5 Basin averaged inter-annual variations of (a) annual average normalized difference vegetation index (NDVI) for the growing season, (b) annual total precipitation for the growing season and (c) annual average temperature for the

growing season for the period 1982–2010 in the Yarlung Zangbo River Basin.

At the pixel scale, the spatial distribution of the average growing season NDVI across the YZRB is shown in Fig. 6. Pixels with multi-year average growing season NDVI values of more than 0.1 are considered to be covered by vegetation. Overall, the multi-year average growing season NDVI values increased gradually from the upper-reaches region to the lower-reaches region of the river basin. In more than half (50.7%) of the YZRB, multi-year average growing season NDVI values ranged from 0.1 to 0.3, with most of these values occurring in the upper- and middle-reaches regions. The pixels with a multi-year average growing season NDVI of 0.3 to 0.6 were mainly located in the middle- and lower-reaches regions, accounting for 33.7% of the basin area. In the southern part of the lower-reaches region and the Yarlung Zangbo Grand Canyon, average growing season NDVI values of more than 0.6 were recorded. Fig. 7 shows the spatial distribution of multi-year average growing season precipitation. From the upper- to lower-reaches regions, precipitation increased gradually. The spatial distribution of multi-year average growing season temperatures in the YZRB is shown in Fig. 8. Temperature also increased gradually from west to east along the YZRB.

Fig. 6 Average growing season normalized difference vegetation index (NDVI) values for 1982–2010 in the Yarlung Zangbo River Basin.

Fig. 7 Average growing season precipitation for 1982–2010 in the Yarlung Zangbo River Basin.

Fig. 8 Average growing season temperature for 1982–2010 in the Yarlung Zangbo River Basin.

The Mann-Kendall test was used to examine the trend in the growing season NDVI of pixels covered by vegetation. The changes in annual growing season NDVI

varied across the study areas (Fig. 9), with 16.8% and 5.3% of the pixels exhibiting significant increasing and decreasing trends, respectively ($P < 0.05$). This result is consistent with the findings for the whole TP that vegetation growth generally improved, but degraded in limited areas (Liu et al., 2013). The pixels with significant decreasing trends are scattered throughout the basin, whereas the pixels with the strongest increasing trends are mainly located within the Nyang subbasin. Our results for annual growing season precipitation indicate that most pixels show no significant trends. The pixels with increasing trends are mainly located within the middle-reaches region, occupying 11.8% of the basin area. All pixels exhibited increasing trends in annual growing season temperature over the period from 1982 to 2010. Given the difference of temporal coverage in the NDVI and meteorological datasets, our analysis covered an almost 30-year period (1982–2010). It is difficult to explore the relationship between the detected trends of these variables and their multi-decadal variability.

Fig. 9 Pixels showing significant increasing or decreasing trends of the growing season normalized difference vegetation index (NDVI) for 1982–2010 at the 0.05 confidence level.

3.2 Variations in the normalized difference vegetation index along elevation and climate gradients

Multi-year average growing season NDVI values for different elevation, precipitation and temperature bands are shown in Fig. 10a–c, respectively. Knowledge of how vegetation changes along elevation and climate gradients is valuable for providing decision support information for ecological restoration and conservation (Fisher and Fule, 2004; Wang et al., 2017). The pattern of elevation-dependent vegetation greening in the YZRB has already been discussed (Li et al., 2015; Li et al. 2016). Our study moves one step further to explore the variations of NDVI along gradients of temperature and precipitation, which was made possible because the satellite based climate dataset has similar spatial resolution (5 km) to that of the GIMMS NDVI dataset (8 km). Generally, our results show that, the NDVI values increase with increasing temperature and precipitation. Meanwhile, NDVI values decrease as elevation increases. Our results highlight variation in the vegetation greenness for a given elevation or climate condition.

Fig. 10 Variations in the multi-year average growing season normalized difference vegetation index (NDVI) for 1982–2010 along (a) elevation, (b) precipitation, and (c) temperature gradients. In these box-and-whisker plots, the box defines the 25th to 75th percentiles, with the median value indicated by a horizontal line in the interior of each box and maximum and minimum values at the whisker ends.

In the upper ranges of temperature and precipitation and lower range of elevations, which are most favorable to vegetation growth, the average NDVI is high and its variation is low. In contrast, in the lower ranges of temperature and precipitation and upper range of elevation, where the environment is unfavorable to vegetation growth, the average of NDVI values are 0.1–0.2. However, the maximum NDVI values attainable in high elevation and low precipitation ranges are much lower than those in the low temperature range, which indicates that compared with temperature, elevation and precipitation both exert stronger constraints on vegetation

growth in the YZRB when they are limiting factors. Elevation is not a factor that directly influences vegetation growth, but the availability of various resources important to vegetation growth, such as light and water, is modulated by elevation and topography (Inouye and Wielgolaski, 2013). Concurrent with decrease in the NDVI as elevation increases, the vegetation type changes from forest to sparse vegetation (Zhang et al., 2007). Our results showed that variation in the NDVI was highest for elevations from 3,000m to 5,000m, consistent with the results of Li et al. (2015) derived from SPOT NDVI for 1999–2013. Especially for the band centered at 3,500m, the high differences in NDVI (with a maximum of about 0.8 and minimum of about 0.1) indicate that vegetation growth conditions varied significantly, which highlights the necessity of exploring the spatial heterogeneity of the relationship between vegetation growth and climate in the YZRB.

Figure 10b shows that the average and maximum NDVI values generally increase as precipitation increases, whereas the minimum NDVI does not show such a trend. When the growing season precipitation is lower than 300 mm, average NDVI values are low and variations in the NDVI are small. In contrast, the variation in the NDVI is much higher when growing season precipitation is greater than 300mm.

Figure 10c demonstrates that when the temperature is greater than 15°C, the NDVI values are higher than 0.6 and their variation is small. These results imply that vegetation growth ceases to be temperature-limited above 15°C in the YZRB. In permafrost regions where temperatures are below 0°C, vegetation growth conditions

are poor. In contrast, for regions with growing season temperatures of 0 to 15°C variations of NDVI in each temperature band are large. This difference suggests that in regions with average growing season precipitation levels of 300–600 mm or temperatures of less than 15°C, vegetation growth has strong spatial variations and is determined by a combination of multiple factors.

3.3 Spatial heterogeneity in relationships between the normalized difference vegetation index and various climatic factors

Fig.11 shows the spatial patterns in partial correlation coefficients between annual average growing season NDVI and annual growing season precipitation. We found that 23.0% and 5.2% of the YZRB exhibited positive and negative correlations between these variables at the 0.05 confidence level, respectively. Their maximum positive and negative correlations coefficients were 0.79 and -0.71, respectively. The pixels with positive correlation were mainly located in the upper-and middle-reaches regions west of Mila Mountain (location shown in Fig. 3), which is located along the border between Lhasa and Nyingchi prefectures and is also the dividing mountain between the Lhasa River and Nyang River. Meanwhile, the pixels with negative correlations were mainly located in the eastern middle- to lower-reaches regions; that is east of Mila Mountain. The spatial distribution of the partial correlation coefficients between the NDVI and temperature is more complex (Fig. 12). Areas of 20.4% and 5.5% exhibited positive and negative correlations, respectively. The pixels with positive correlations were mainly located in the upper-reaches region as well as parts

of the middle-reaches region east of Mila Mountain. In contrast, pixels with negative correlations were mainly located in the area around the mainstream in the western part of the middle-reaches region, the Lhasa subbasin, and the low-altitude parts of the lower-reaches region.

Our results suggest that the relationship between the NDVI and temperature is inconsistent within the dry region of the YZRB, which includes the upstream region and the parts of the middle-reaches region west of Mila Mountain. Under the continental plateau climate, there is limited precipitation linked to the Indian monsoon, because of the barrier effect of the mountains (Sang et al., 2016). Therefore, water is the limiting factor for vegetation growth. This factor explains the strong positive correlation between the NDVI and precipitation in this area. However, the relationship between the NDVI and temperature varied across this region. In the upper-reaches region where it is extremely dry and cold in all seasons, positive correlations were detected. In this area, higher temperatures would produce more snow-melt water for vegetation to use, which is one possible explanation for this phenomenon. In contrast, in the semi-arid middle-reaches region west of Mila Mountain, including the Nyangqu and Lhasa subbasins, negative correlations were found. In this region, aridity is lower and temperature is higher, with more water available for plant growth than in the upper-reaches region. Soil water deficit is considered to be a major factor restricting plant growth in this region (Zhong et al., 2014). Higher temperatures during the growing season would increase the amount of water evaporated from the soil,

lowering available water for vegetation growth and consequently restricting vegetation activity (Jobbágy et al., 2002; Piao et al., 2006). Another possible reason is that in the semi-arid regions of the TP, earlier snow-melting due to higher temperatures would reduce the snow cover shielding plants from low temperatures and increase the risk of frost damage in early spring (Wang et al., 2017; Rammig et al., 2010). Several studies (Poulter et al., 2014; Ukkola et al., 2016) have shown that in semi-arid regions, rising atmospheric CO₂ has led to observable changes in terrestrial ecosystems and consequently to changes in the water cycle. To further unravel the complex driving mechanisms of plant growth in the semi-arid region of the YZRB as well as effects of these changes in vegetation growth on the water cycle, long-term in-situ plant physiological observations and snow observations are necessary.

One limitation of this study is that, although the reliability of the climate data used in this study has been verified by Gao et al. (2015) and Fan et al. (2018) using ground observations in the TP, uncertainties and biases of this dataset are not thoroughly understood. This is because the quality of these data can only be evaluated at sparsely distributed meteorological stations. Clearly, a ground observation network with denser spatial coverage is highly desirable for the YZRB. What is promising from the results of this study is that, compared with earlier studies of the YZRB (Xu et al., 2013; Li et al., 2015; Han et al., 2018), we were able to identify the spatial heterogeneities of factors driving vegetation growth at a finer scale, because of the use of data with high spatial resolution (relative to the global or ground-based data). Our

study reveals the necessity of conducting similar studies using high-resolution climatic datasets to evaluate spatial patterns of the hydrological implications of climate influences on vegetation at the basin or regional scales, especially in regions where ground observations are unavailable. Furthermore, the scheme adopted in this study could be used to detect regions where interactions between vegetation and hydrological processes are unique and deserve more mechanistic studies.

Fig. 11 Pixels for which partial correlation coefficients between the annual average growing season normalized difference vegetation index (NDVI) and annual growing season precipitation for 1982–2010 are significant at the 0.05 confidence level.

Fig. 12 Pixels for which partial correlation coefficients between the annual average growing season normalized difference vegetation index (NDVI) and annual growing season temperature for 1982–2010 are significant at the 0.05 confidence level.

4 Conclusions

As a key component of ecohydrological processes, changes in vegetation growth status influence the efficiency of plant water use and potentially affect water resources. This study explored changes in vegetation growth and their driving mechanisms in the highest basin in the world, the YZRB, based on the GIMMS NDVI product and a satellite-based climatic dataset with finer resolution than data derived from in-situ meteorological stations in the YZRB or global datasets of coarse resolution. This enabled us to explore the spatial heterogeneity of factors influencing vegetation growth within this internationally important and unique basin. Our results revealed that at the basin scale, growing season NDVI and precipitation showed non-significant increasing trends, whereas temperature showed a significant increasing trend over the past three decades. At the pixel scale, 16.8% and 5.3% of the YZRB by area exhibited increasing and decreasing trends, respectively. The highest increases of the NDVI occurred within the Nyang subbasin. The NDVI showed large variation in middle ranges of elevation and climate gradients, which implies that vegetation growth in these ranges was highly variable spatially. Partial correlation analyses between the NDVI and climate indicated that the driving mechanisms of vegetation growth changed with aridity, with more complex relationship in the semi-arid region. In the future, additional works combining process-based ecosystem models and ground observations would be very valuable for assessing the contribution of each possible driving factor to vegetation growth in the YZRB.

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References

- Anderson, R.G., Canadell, J. G., Randerson, J. T., Jackson, R. B., Hungate, B. A., Baldocchi, D. D., Ban-Weiss, G. A., Bonan G. B., Caldeira, K., Cao, L., Diffenbaugh, N. S., Gurney, K. R., Kueppers, L. M., Law, B. E., Luyssaert, S., O'Halloran, T. S., 2011. Biophysical considerations in forestry for climate protection. *Front. Ecol. Environ.* 9 (3), 174-182. <https://doi.org/10.1890/090179>.
- Arora, V., 2002. Modeling vegetation as a dynamic component in soil-vegetation-atmosphere transfer schemes and hydrological models. *Rev. Geophys.* 40(2). DOI: 10.1029/2001RG000103.
- Benjamin, P., David, F., Philippe, C., Ranga, B.M., Niels, A., Bi, J., Gregoire, B., Josep, G. C., Frederic, C., Liu, Y., Steven, W. R., Stephen, S., Guido, R. W., 2014. Contribution of semi-arid ecosystems to interannual variability of the global carbon cycle. *Nature*. 509, 600-603.

- Fan, J., Sun, W., Zhao, Y., Xue, B., Zuo, D., Xu, Z., 2018. Trend analyses of extreme precipitation events in the Yarlung Zangbo River Basin, China using a high-resolution precipitation product. *Sustainability*. 10 (5), 1396. <https://doi.org/10.3390/su10051396>.
- Fensholt, R., Langanke, T., Rasmussen, K., Reenberg, A., Prince, S. D., Tucker, C., Scholes, R. J., Le, Q. B., Bondeau, A., Eastman, R., Epstein, H., Gaughan, A. E., Hellden, U., Mbow, C., Olsson, L., Paruelo, J., Schweitzer, C., Seaquist, J., Wessels, K., 2012. Greenness in semi-arid areas across the globe 1981-2007—an Earth Observing Satellite based analysis of trends and drivers. *Remote Sens. Environ.* 121 (2), 144-158. <https://doi.org/10.1016/j.rse.2012.01.017>.
- Fisher, M.A., Fule, P.Z., 2004. Changes in forest vegetation and arbuscular mycorrhizae along a steep elevation gradient in Arizona. *Forest. Ecol. Manag.* 200(1-3), 293-311. DOI: 10.1016/j.foreco.2004.07.003.
- Fu, Y., Campioli, M., Vitasse, Y., Boeck, H. J. D., Berge, J. V., Abdelgawad, H., Asard H., Piao, S., Deckmyn, G., Janssens, I. A., 2014. Variation in leaf flushing date influences autumnal senescence and next year's flushing date in two temperate tree species. *P. Natl Acad. Sci. U.S.A.* 111(20), 7355-60. <https://doi.org/10.1073/pnas.1321727111>.
- Gao, Y., Li, K., Chen, F., Jiang, Y., Lu, C., 2015. Assessing and improving Noah-MP land model simulations for the central Tibetan Plateau. *J. Geophys. Res.* 120, 9258–9278.

- Guo B, Han F, Jiang, L.2018. An Improved Dimidiated Pixel Model for Vegetation Fraction in the Yarlung Zangbo River Basin of Qinghai-Tibet Plateau. *J. Indian Soc. Remote.* 46(2), 219-231.
- Han, X., Zuo, D., Xu, Z., Cai, S., Gao, X.,2018. Analysis of vegetation condition and its relationship with meteorological variables in the Yarlung Zangbo River Basin of China. *IAHS Publication.*379, 105–112.
- Holben, B.N., 1986. Characteristics of maximum-value composite images from temporal AVHRR data. *Int. J. Remote Sens.* 7(11), 1417-1434.
- Inouye D.W., Wielgolaski F. E., 2013. Phenology at high altitudes, in: Schwartz, M. D. (Eds.), *Phenology: An Integrative Environmental Science*. Dordrecht: Springer Netherlands, pp. 249–72.
- Jackson, R. B., Randerson, J. T., Canadell, J. G., Anderson, R. G., Avissar, R., Baldocchi, D. D, Bonan, G. B., Caldeira, K., Diffenbaugh, N. S., Field, C. B., Hungate, B. A., Jobbágy, E. G., Kueppers, L. M., Noretto, M. D., Pataki, D. E., 2008. Protecting climate with forests. *Environ. Res. Lett.* 3 (4), 269-269.
- Jobbágy, E.G., Sala, O.E., Paruelo, J.M., 2002. Patterns and controls of primary production in the Patagonian Steppe: a remote sensing approach. *Ecology.* 83(2), 307-319.
- Kang, Q., Shi, C., Yan, H., Yu, P.,2007. Climate change over the Yarlung Zangbo River Basin during 1961-2005. *J. Geogr. Sci.* 17(4), 409-420.
- Kendall MG., 1975. *Rank Correlation Methods*: Griffin

- Kenett, D. Y., Tumminello, M., Madi, A., Gur-Gershgoren, G., Mantegna, R. N., Ben-Jacob, E., 2010. Dominating Clasp of the Financial Sector Revealed by Partial Correlation Analysis of the Stock Market. *Plos One*. 5(12): e15032. <https://doi.org/10.1371/journal.pone.0015032>.
- Leakey, A.D.B., Ainsworth, E.A., Bernacchi, C.J., Rogers, A., Long, S.P., Ort, D.R., 2009. Elevated CO₂ effects on plant carbon, nitrogen, and water relations: six important lessons from FACE. *J. Exp. Bot.* 60(10), 2859-2876.
- Le Quéré, C., Andrew, R. M., Friedlingstein, P., Sitch, S., Pongratz, J., Manning, A. C., Korsbakken, J. I., Peters, G. P., Canadell, J. G., Jackson, R. B., Boden, T. A., Tans, P. P., Andrews, O. D., Arora, V. K., Bakker, D. C. E., Barbero, L., Becker, M., Betts, R. A., Bopp, L., Chevallier, F., Chini, L. P., Ciais, P., Cosca, C. E., Cross, J., Currie, K., Gasser, T., Harris, I., Hauck, J., Haverd, V., Houghton, R. A., Hunt, C. W., Hurtt, G., Ilyina, T., Jain, A. K., Kato, E., Kautz, M., Keeling, R. F., Klein Goldewijk, K., Körtzinger, A., Landschützer, P., Lefèvre, N., Lenton, A., Lienert, S., Lima, I., Lombardozzi, D., Metzl, N., Millero, F., Monteiro, P. M. S., Munro, D. R., Nabel, J. E. M. S., Nakaoka, S.-I., Nojiri, Y., Padin, X. A., Peregon, A., Pfeil, B., Pierrot, D., Poulter, B., Rehder, G., Reimer, J., Rödenbeck, C., Schwinger, J., Séférian, R., Skjelvan, I., Stocker, B. D., Tian, H., Tilbrook, B., Tubiello, F. N., van der Laan-Luijkx, I. T., van der Werf, G. R., van Heuven, S., Viovy, N., Vuichard, N., Walker, A. P., Watson, A. J., Wiltshire, A. J., Zaehle, S., Zhu, D., 2018. Global Carbon Budget . *Earth. Syst. Sci. Data*. 10,

405-448.<https://doi.org/10.5194/essd-10-405-2018>.

Li, F., Zhang, Y., Xue Z., Teng, J., Liu C., Liu, W., Mpelasoka, F., 2013. The impact of climate change on runoff in the southeastern Tibetan Plateau. *J. Hydrol.* 505(505), 188-201. <https://doi.org/10.1016/j.jhydrol.2013.09.052>.

Li, H., Li, Y., Shen, W., Li, Y., Lin, J., Lu, X., Xu, X., 2015. Elevation-Dependent Vegetation Greening of the Yarlung Zangbo River Basin in the Southern Tibetan Plateau, 1999-2013. *Remote Sens.* 7 (12), 16672-16687. <https://doi.org/10.3390/rs71215844>.

Li, H., Jiang J., Chen, B., Li, Y., Xu, Y., Shen, W., 2016. Pattern of NDVI-based vegetation greening along an altitudinal gradient in the eastern Himalayas and its response to global warming. *Environ. Monit. Assess.* 188 (3), 186.<https://doi.org/10.1007/s10661-016-5196-4>.

Liu, J., Gao, J. and Wang, W., 2013. Variations of vegetation coverage and its relations to global climate changes on the Tibetan Plateau during 1981-2005. *J Mt. Sci.* 31 (2), 234-242. (In Chinese with English abstract).

Liu, Z., Yao, Z., Huang, H., Wu, S., Liu, G., 2014. Land use and climate changes and their impacts on runoff in The Yarlung Zangbo river basin, China. *Land. Degrad. Dev.* 25(3), 203-215.

Mann, H.B., 1945. Nonparametric tests against trend. *Econometrica.* 13(3), 245-259.

Myneni, R.B., Keeling, C.D., Tucker, C.J., Asrar, G., Nemani, R.R., 1997. Increased plant growth in the northern high latitudes from 1981 to 1991. *Nature.*

386(6626),698-702. DOI: 10.1038/386698a0.

- Piao, S., Mohammat, A., Fang, J., Cai, Q., Feng, J., 2006. NDVI-based increase in growth of temperate grasslands and its responses to climate changes in China. *Glob. Environ. Chang.* 16(4), 340-348. <https://doi.org/10.1016/j.gloenvcha.2006.02.002>.
- Piao, S., Wang, X., Ciais, P., Zhu, B., Wang, T., Liu, J., 2011. Changes in satellite-derived vegetation growth trend in temperate and boreal Eurasia from 1982 to 2006. *Glob. Change Biol.* 17 (10), 3228-3239. <https://doi.org/10.1111/j.1365-2486.2011.02419.x>.
- Rammig, A., Jonas, T., Zimmermann, N.E., Rixen, C., 2010. Changes in alpine plant growth under future climate conditions. *Biogeosciences*. 7(6),2013-2024.
- Sang, Y. F., Singh, V. P., Gong, T., Xu, K., Sun, F., Liu, C., Liu, W., Chen, R., 2016. Precipitation variability and response to changing climatic condition in the Yarlung Tsangpo River basin, China. *J. Geophys. Res.* 121, 8820–8831.
- Sen, P.K., 1968. Estimates of the regression coefficient based on Kendall's tau. *J. Am. Stat Assoc.* 63(324), 1379-1389.
- Sun, W., Song, H., Yao, X., Ishidaira, H. Xu, Z., 2015. Changes in Remotely Sensed Vegetation Growth Trend in the Heihe Basin of Arid Northwestern China. *Plos One*. 10(8), e0135376. <https://doi.org/10.1371/journal.pone.0135376>.
- Tan, K., Ciais, P., Piao, S., Wu, X., Tang, Y., Vuichard, N., Liang, S., Fang, J., 2010. Application of the ORCHIDEE global vegetation model to evaluate biomass and

- soil carbon stocks of Qinghai-Tibetan grasslands. *Global. Biogeochem. Cy.* 24, GB1013. <https://doi.org/10.1029/2009GB003530>.
- Tao, J., Zhang, Y., Dong, J., Fu, Y., Zhu, J., Zhang, G., Jiang, Y., Tian, L., Zhang, X., Zhang, T., Xi, Y., 2015. Elevation-dependent relationships between climate change and grassland vegetation variation across the Qinghai-Xizang Plateau. *Int. J. Climatol.* 35 (7), 1638-1647. <https://doi.org/10.1002/joc.4082>.
- Tong, K., Su, F., Yang, D., Zhang, L. and Hao, Z., 2014. Tibetan Plateau precipitation as depicted by gauge observations, reanalyses and satellite retrievals. *Int. J. Climatol.* 34 (2), 265-285. <https://doi.org/10.1002/joc.3682>.
- Ukkola, A. M., Prentice, I. C., Keenan, T. F., Dijk, A. I. J. M. V., Viney, N. R., Myneni, R. B., Bi, J., 2016. Reduced streamflow in water-stressed climates consistent with CO₂ effects on vegetation. *Nat. Clim. Change.* 6(1). DOI: 10.1038/nclimate2831.
- Vicuna, S., Dracup, J.A., Lund, J.R., Dale, L.L., Maurer, E.P., 2010. Basin-scale water system operations with uncertain future climate conditions: Methodology and case studies. *Water Resour. Res.* 46(W04505). DOI: 10.1029/2009WR007838.
- Wang, C., Wang, S., Fu, B.J., Li, Z.S., Wu, X., Tang, Q., 2017. Precipitation gradient determines the tradeoff between soil moisture and soil organic carbon, total nitrogen, and species richness in the Loess Plateau, China. *Sci. Total. Environ.* 575, 1538-1545. DOI: 10.1016/j.scitotenv.2016.10.047.

- Wang, S., Wang, X., Chen, G., Yang, Q., Wang, B, Ma, Y., Shen, M., 2017. Complex responses of spring alpine vegetation phenology to snow cover dynamics over the Tibetan Plateau, China. *Sci. Total. Environ.* 575, 1538-1545. DOI: 10.1016/j.scitotenv.2016.10.047
- Xu, Z., Liu, W., Li, F., Liu, P., 2013. Vegetation change and its relationship with precipitation on the southern Tibetan Plateau. *IAHS Publication*. 359, 418-424.
- Zeng, C., Zhang, F., Lu, X., Wang, G., Gong, TL. 2018. Improving sediment load estimations: The case of the Yarlung Zangbo River (the upper Brahmaputra, Tibet Plateau). *Catena*. 160, 201-211. DOI: 10.1016/j.catena.2017.09.023
- Zhang, G., Zhang, Y., Dong, J. Xiao, X., 2013. Green-up dates in the Tibetan Plateau have continuously advanced from 1982 to 2011. *P. Natl. Acad. Sci. USA*. 110 (11), 4309-4314. <https://doi.org/10.1073/pnas.1210423110>.
- Zhang, W., Zhang, Y., Wang, Z., Ding, M., Yang, X., Lin, X., Liu, L., 2007. Vegetation change in the Mt. Qomolangma Nature Reserve from 1981 to 2001. *J. Geo. Sci.* 17 (2), 152–164.
- Zhong, L., Ma, Y., Fu, Y., Pan, X., Hu, W., Su, Z., Salama, M. S., Lu, F., 2014. Assessment of soil water deficit for the middle reaches of Yarlung-Zangbo River from optical and passive microwave images. *Remote Sens. Environ.* 142 (3), 1-8.

Declaration of interests

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

paper.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: