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Wetland vegetation changes in response to climate change and human activities on the Tibetan Plateau during 2000–2015

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The Tibetan Plateau (TP), known as the third pole, is the highest plateau in the world. It has numerous wetlands, which are important ecological security barriers and plays an important role in mitigating global climate change. This paper employed breaks for additive seasonal and trend (BFAST) algorithm for the mutation detection of the monthly normalized difference vegetation index (NDVI) in wetlands. In addition, correlation analysis and residual analysis were used to study the response of climate change and human activities to NDVI of alpine wetland vegetation in the TP during 2000–2015. The results indicate that the NDVI showed a weak upward trend of 0.009/10a ($P < 0.05$) with the climate presenting a trend of dry heat development. The NDVI of the growing season was greatly affected by temperature factors with the highest correlation coefficient of 0.686 ($P < 0.01$). The temperature in the month before and solar radiation in the 3 months before also presented a time lag effect on NDVI, and their correlation coefficients were 0.574 ($P < 0.05$) and 0.636 ($P < 0.05$), respectively. Additionally, human activities may have a positive impact on the wetland after 2008. This study explored, for the first time, the NDVI variations of the dynamic wetland and their correlations with temperature, precipitation and solar radiation.

KEYWORDS

NDVI, climate change, human activities, the Tibetan Plateau, BFAST, correlation analysis

1. Introduction

With the process of global warming, ecosystems are affected by more and more natural and human factors. Studies have shown that climate variation can change vegetation coverage (Timoney et al., 2019; Wen et al., 2019; Rezaei and Gurdak, 2020; Goodwin et al., 2021). The Tibetan Plateau (TP) is an eco-sensitive area to climate change (Wei and Wu, 2021). Wetlands provide immense storage of carbon that, if released with climate shifts, could accelerate those changes (Mitsch et al., 2009). Climate change threatens terrestrial water storage and Himalayan plant species over the TP (Salick et al., 2014; Li et al., 2022). As the third pole, the TP has the largest wetland area in China, which may significantly affect the TP's vegetation (Yuan et al., 2014; Wang et al., 2020). The threat of climate change is considered to be a major factor that can affect the function and biogeochemistry of wetlands (Salimi et al., 2021). In the case of the Alpine wetland, it is vulnerable to low temperatures, strong evapotranspiration, large direct radiation and special ecological environments (including glaciers, frozen soils, deserts, meadows, etc.) (Kraaijenbrink et al., 2017; Dakhil et al., 2019; Wei and Wu, 2021).

Although the response of vegetation to climate change has become a hot topic of the research of the TP, most of them focus on grassland or forest ecosystems (Ding et al., 2013; Yi et al., 2014; Sun et al., 2016; Wang et al., 2016; Dakhil et al., 2019; Xiong et al., 2019). Therefore, in the context of climate variation, clarifying the response of wetland vegetation to climatic change in the TP is crucial.

For the study of wetland vegetation on the TP, Shen et al. (2022) (Kun et al., 2020) found that vegetation growth was influenced by temperature and precipitation, but the limitation is that the wetland extent in their research was fixed. A study (Xue et al., 2018) revealed that the wetlands on the TP have started to deteriorate. About 6.4% of their area has been lost from the 1970s to 2010s. In fact, wetland space is dynamic and changing. With this in mind, we discussed the vegetation cover status of the changing wetlands year by year.

For meteorological research, we not only discussed temperature and precipitation like others (Wang et al., 2011; Guo et al., 2014; Jiang et al., 2017; Shen et al., 2022), but also added solar radiation. The TP has abundant solar energy resources because of its high elevation (Wang and Qiu, 2009). Solar radiation plays a critical role in hydrological cycling, vegetation growth, climate, weather change, and so on (Yaghoubi and Sabzevari, 1996; Zhou et al., 2010; Yue and Huang, 2011; Colak et al., 2013). What's more, scholars have studied the time-lag effect of climate (Bao et al., 2014; Diao et al., 2021; Zuo et al., 2021). Richard and Pocard (1998) and Zhe and Zhang (2021) used correlation coefficients to investigate the relationship between climate and the Normalized Difference Vegetation Index (NDVI), attesting a time response of the current and previous months. Guo et al. (2014) also found the time-lag effect of NDVI response to climate change, while the study area was in the semiarid region of the TP. Currently, the time-lag effects are still poorly understood in alpine wetland vegetation.

The alpine wetland vegetation is facing more severe and variable climatic conditions as well as complex ecosystems. In this study, monthly NDVI data and various meteorological data from 2000 to 2015 were used to analyze the vegetation greenness of the wetlands in the TP for a long time series by the breaks for additive seasonal and trend (BFAST) model and other methods. The main objective of our investigation has been to reveal the tipping points (Lenton, 2013) of wetland greenness and climate in the new century, and to explain the extent of climate change and human activities on alpine vegetation. In addition, the time-lag effects of alpine vegetation on climate variables can be further discussed by investigating the temporal pattern in NDVI of the vegetation growing season. This research is expected to provide scientific reference for vegetation protection, ecological management and rational development in this area under the background of climate change.

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) is located in the southwest of China (Figure 1), about 2,945 km long from east to west and 1,532 km long from north to south (Chen et al., 2021). Due to its high elevation, this region has quite cold winters, mild summers and large diurnal temperature variations (Xiong et al., 2019) and the solar radiation of the TP is

relatively high (Zhou et al., 2010). The annual average temperature is approximately between -5 and 8°C (Xin et al., 2008; Wang and Han, 2012). The inter-annual variation in temperature on the TP is small but the diurnal variation is large (Kirillin et al., 2021; Zhang et al., 2021). Known as the water towers of Asia (Yao et al., 2022), however, most of the TP is an arid and semi-arid region with not much precipitation (Zhang et al., 2000). The annual precipitation on the TP is about 400 mm, and there are significant seasonal differences in precipitation (Wang and Han, 2012; Wang et al., 2021). Spring and winter are the driest seasons on the annual scale. The main land use type in the area is grassland, followed by forest (Tang et al., 2018).

2.2. Data

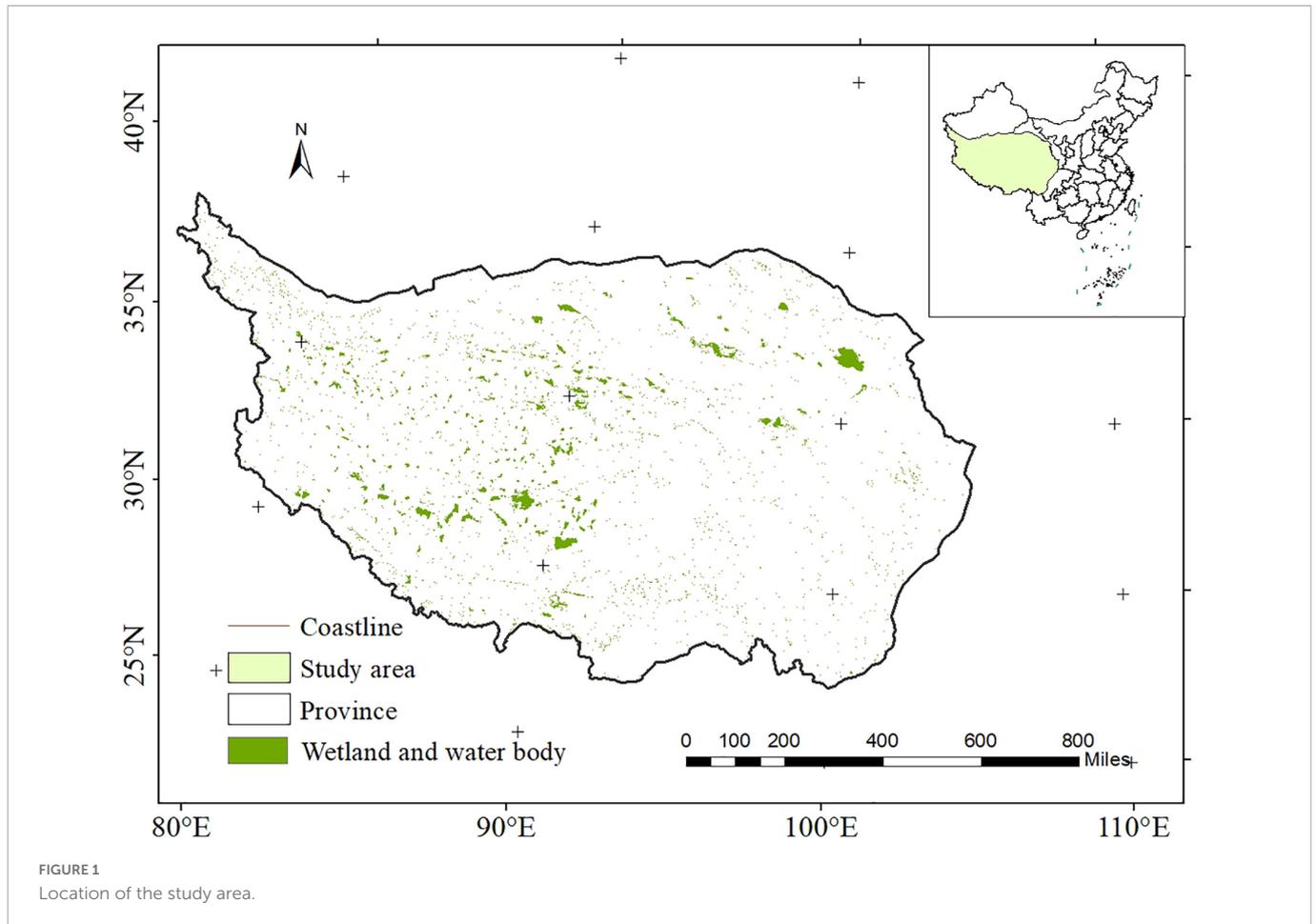
Land use data (Xu et al., 2021) were obtained through Google Earth Engine (GEE) platform with a spatial resolution of 30 m. The User's Accuracy (UA) of wetland for this data set is higher, with UA of 71.06%, compared with datasets like Globeland30, FROM-GLC, and GLC-FCS30 (UA of 52.23, 29.25, and 47.17%, respectively). What's more, the kappa coefficient for Asian reached 0.72 and the UA for the land use type of wetland reached 76.09%. In this paper, we yearly extracted the wetland and water body data from 2000 to 2015 as a mask for analyzing NDVI changes.

The vegetation index can reflect the vegetation cover, among which, NDVI is the best indicator to reflect the vegetation growth condition and vegetation cover. In this paper, the continuous time series SPOT/VEGETATION NDVI satellite remote sensing data were used to synthesize the 10 days NDVI data into monthly data by using the maximum-value composition (MVC) (Holben, 1986) technique, and was free downloaded from the Resource and Environment Data Cloud Platform, Chinese Academy of Sciences¹ with a 1 km resolution from 2000 to 2015 (Xu, 2018). In order to avoid the interference of non-vegetation information on the alpine wetland vegetation NDVI with reference (Yu et al., 2012; Ding et al., 2013; Kun et al., 2020) to the previous vegetation NDVI thresholds on the TP, the data in this research must meet certain requirements as follows: (1) the average value of NDVI in April-September shall be more than 0.10; (2) the value of NDVI shall exceed than 0; (3) the average value of NDVI in winter shall be less than 0.4; (4) June to October was selected as the length of growth season (LOG) for analyzing whether there is a hysteresis response of NDVI to climate.

The meteorological data used were monthly precipitation (Peng, 2020), temperature (Peng, 2019), and solar radiation (Feng and Wang, 2020) data from 2000 to 2015 from the National Tibetan Plateau/Third Pole Environment Data Center.² The spatial resolution of precipitation data and average temperature data is 1 km, and the resolution of solar radiation data is 10 km. For further comparing the impacts of seasonal climate factors on NDVI, we calculated the average values of climate factors during spring (March, April, and May), summer (June, July, and August), autumn (September, October, and November), and winter (December, January, and February).

1 <http://www.resdc.cn>

2 <http://data.tpedc.ac.cn/zh-hans/>



2.3. Methodology

2.3.1. Mutation detection

For this study, the BFAST algorithm was used to analyze the abrupt change characteristics of vegetation greenness in alpine wetlands between 2000 and 2015. BFAST was first proposed in 2010 to make vegetation disturbance identification well in remote sensing data identification (Verbesselt et al., 2010b), and now the algorithm is used in several fields (Wang et al., 2014; Fang et al., 2018; Gholamnia et al., 2019), including climate analysis, hydrological analysis, and economic analysis. In this study, the BFAST package in R statistical software is used to obtain the tipping points of monthly NDVI of wetlands on the TP from 2000 to 2015, which can provide an analysis of the effect of climate anomalies on vegetation greenness and also help to research whether there is a lag period in the effect of climate on vegetation greenness. Formula is as follows (Verbesselt et al., 2010a):

$$Y_t = T_t + S_t + e_t \quad (t = 1, \dots, n) \quad (1)$$

where Y_t is the observed data at time t ; T_t is the fitted trend component; S_t is the fitted seasonal component; e_t is the remainder component; n is the total number of observed data. The BFAST procedures (Watts and Laffan, 2014) use a parameter known as h to determine the maximum number of breaks in the data set. This parameter can help in detecting trend changes. Following their work and the recommendations by Verbesselt et al. (2010b) and Fang et al. (2018), we hypothesized that the minimum interval between adjacent abrupt changes was approximately 2 years within a 16-year time series

(2000–2015) in this study, therefore, $h = 0.13$ was used. Besides, the “harmonic” seasonal model was chosen for natural vegetation, while the “dummy” model is often used for cropland (Verbesselt et al., 2010a).

What’s more, based on the correlation between climate and NDVI, we used the Mann–Kendall mutation test (Kendall, 1938; Shadmani et al., 2012) to calculate the tipping points in meteorology and verify the wetland vegetation changes in response to climate change.

2.3.2. Correlation analysis

Pearson’s correlation coefficients were calculated for examining the relationship between NDVI (during vegetation growing season, from June to October) and precipitation, average temperature, solar radiation in the current month, the first month before, the first 2 months before and the first 3 months before. This research used this common method of testing correlation to analyze the time lag effect of vegetation response to climate. The calculation steps are as follows (Xiong et al., 2019):

$$r = \frac{\text{cov}(x, y)}{\sqrt{\text{cov}(x, x)\text{cov}(y, y)}} \quad (2)$$

where r is the linear correlation coefficient; cov is the covariance; x is the NDVI value; y is the precipitation (mm), temperature ($^{\circ}\text{C}$), or solar radiation (W/m^2). The value of r ranges from -1 to 1 , and the larger the absolute value, the higher the degree of correlation.

If $r < 0$, it indicates that the index promotes NDVI; otherwise, it inhibits NDVI.

2.3.3. Residual analysis

One of the most important factors that can affect the vegetation of a region is climate change. The residual analysis method can also separate the effects of human activities from those caused by environmental changes (Evans and Geerken, 2004). The predicted value of NDVI is fitted by meteorological factors, which is the amount of climate change impact. The difference between the calculated value and the true value of NDVI can be considered as the influence of human factors. This method is called residual analysis and has been widely used (Herrmann et al., 2005; Higginbottom and Symeonakis, 2014; Fernández-Giménez et al., 2017; Jiang et al., 2017; Chu et al., 2019). It can be presented using the following equation:

$$\varepsilon = NDVI_{real} - NDVI_{pre} \quad (3)$$

where ε is the NDVI residual; $NDVI_{real}$ is the true value of NDVI; $NDVI_{pre}$ is the predicted value of NDVI. If $\varepsilon > 0$, it indicates that human activities have a positive impact; if $\varepsilon < 0$, it indicates human activities produce negative effects; if $\varepsilon = 0$, indicating that the impact of human activities is relatively weak. If the residuals trend is significant, the NDVI variations can be explained by human activities (Jiang et al., 2017; Chu et al., 2019).

3. Results

3.1. Analysis of vegetation greenness changes in alpine wetlands

As shown in Figure 2, the NDVI of wetland vegetation in the TP was relatively small and changed gently until May, generally between 0.1 and 0.2. After May, the surface vegetation in the region increased rapidly, reaching a maximum in July and August. Then, it gradually decreased and dropped below 0.2. It can be seen that the growing season of wetland vegetation in the TP was more consistent with the description of vegetation in this region starting to germinate and grow in May and dying off by mid-late October in other article (Ding et al., 2013), indicating that the NDVI reflection of plant growth is consistent with other observations. Comparing Figures 2A, B the month-by-month trend of NDVI was approximately the same, but during the vegetation growing season, the values of NDVI in the wetland were significantly higher than the overall regional NDVI values. This may be due to the fact that a large area of the TP is covered with grassland vegetation, and wetlands have relatively sufficient water compared to arid grassland ecosystems, which promotes the growth of vegetation in wetland (Piao et al., 2007).

For interannual variability, the study found that the area of wetlands was constantly undergoing changes, from 1,069.16 in 2000 to 1,100.49 km² in 2015, increasing year by year. Not only the increase in wetland area, but also the increase of NDVI within the wetland area. The monthly NDVI values of wetlands in the TP from 2000 to 2015 were examined according to the BFAST model method, and in the overall time series analysis, the NDVI values showed an overall increasing trend. The trend was detected in the trend term, in which a tipping point was observed between 2013 and 2014 (Figure 3). Original time series (Y_t) and seasonal component (S_t) showed cyclic

regular changes, indicating that vegetation is suitable for long-term monitoring and research. The dashed line in Tt represents the times of abrupt change in NDVI in the trend components. There was one break, which was in 2013 with the largest magnitude (-0.013). Time of the biggest change detected in the trend component was 165th data, corresponding to September in 2013, and the broad time range was from February 2013 to January 2014.

It can be seen from Figure 4 that the annual mean NDVI of alpine wetland vegetation also showed a weak upward trend of 0.009/10a ($P < 0.05$). The mean NDVI in spring, summer and autumn also increased, on the contrary, the mean NDVI in winter showed a downward trend. This is also consistent with the NDVI change of the entire TP (Sun and Qin, 2016). The mean NDVI in autumn and winter varied greatly with R squared values of 0.01573 and 0.07625, respectively, and p values of 0.6435 and 0.3005, respectively. The mean NDVI values in spring ($P < 0.01$) were smaller than those in summer ($P < 0.01$), implying that the response of vegetation to climate may not be as pronounced. Summer is in the vegetation growing season, therefore, the reliability of this paper in studying the relationship between climatic factors and NDVI by using the vegetation growing season is further verified.

3.2. Analysis of climate change characteristics

There is no doubt that the climate in the TP has changed under the condition of global warming. The interannual and seasonal trends of temperature, precipitation and solar radiation in the wetlands of the TP from 2000 to 2015 are shown in Figure 5, and Table 1 shows the statistical interannual and seasonal climate tendency rates of these meteorological elements.

The annual mean temperature of the wetlands was similar to the spring and autumn mean temperatures (all of them were around 0°C), displaying an increasing trend with a climatic tendency rate of 0.04, 0.27, and 0.13°C/10a, respectively. In contrast, the mean temperature in summer and winter showed a decreasing trend with a faster decrease in winter ($-0.52^\circ\text{C}/10\text{a}$). In general, the warming in spring and autumn contributed more to the annual mean temperature change, giving a slightly increasing trend.

Precipitation was less in 2002, 2006, and 2015, not exceeding 130 mm, with more pronounced fluctuations. In general, it represented a decreasing trend with a climatic tendency rate of about -1.83 mm/10a. Except for summer, seasonal changes in precipitation could be seen as an overall decreasing trend, only with slightly different magnitudes, with the fastest decrease in spring (-1.67 mm/10a) and the slowest decrease in autumn (-0.14 mm/10a). Rainfall in winter was scarce, with a multi-year average of 4.75 mm, and also showed a decreasing trend (-0.3 mm/10a). Summer showed a slightly increasing trend with a climatic tendency rate of 0.27 mm/10a. Although precipitation in summer was an increasing trend, the increase was small and much less than the decrease in precipitation in other seasons. It is worth mentioning that the variation in precipitation was greater than the variation in temperature in each season, which may be due to changes in the monsoon system in East Asia (Wang et al., 2011).

Solar radiation displayed an increasing trend with a climatic tendency rate of about 2.27 W/m²/10a. Unlike the seasonal overall

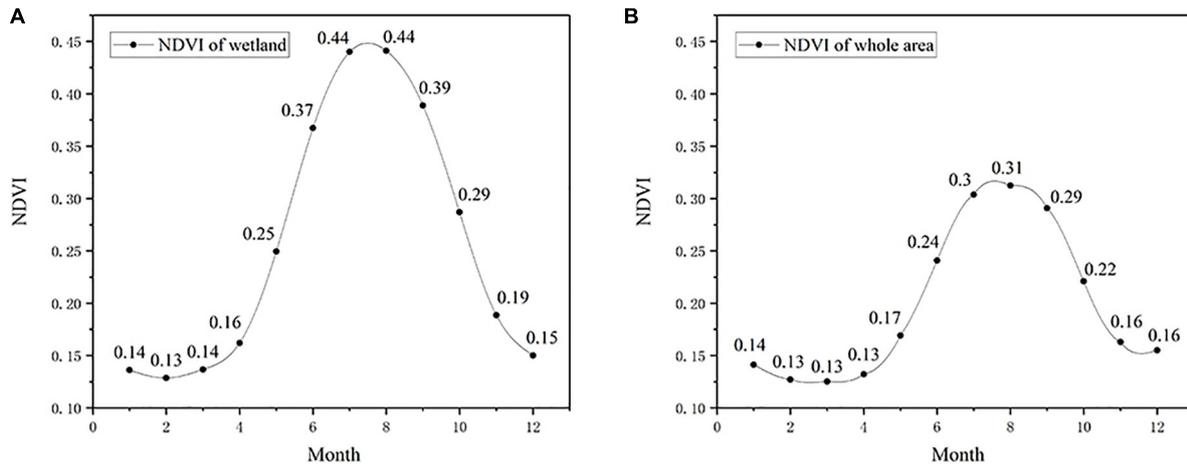


FIGURE 2

The multi-yearly seasonal variation for (A) averaged normalized difference vegetation index (NDVI) of wetland and (B) averaged NDVI in the TP.

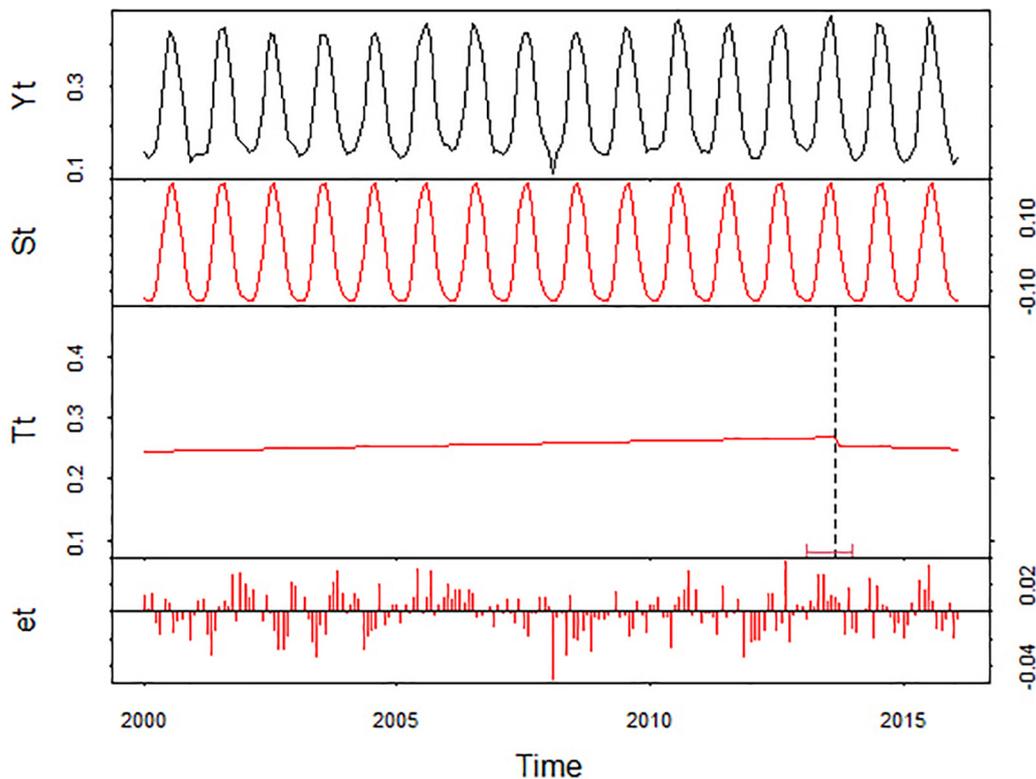


FIGURE 3

Breaks for additive seasonal and trend (BFAST) breakdown of normalized difference vegetation index (NDVI) time series for the 2000–2015 period for alpine wetland vegetation in TP.

decreasing trend in precipitation, the seasonal differences in solar radiation were more pronounced. There was a decreasing trend in autumn ($-0.68 \text{ W/m}^2/10\text{a}$) and winter ($-0.99 \text{ W/m}^2/10\text{a}$). Solar radiation exceeded 250 W/m^2 in both spring ($1.51 \text{ W/m}^2/10\text{a}$) and summer ($2.42 \text{ W/m}^2/10\text{a}$), and contributed more to the annual solar radiation variation.

In summary, the trends of the three meteorological elements show that climate change in the alpine wetlands of the TP had a tendency to develop toward dryness and heat.

3.3. Correlation analysis of NDVI and climatic factors

There is a correlation between climate and NDVI, which may be due to a certain degree of lag of vegetation growth on climate environment. For example, in case of heavy snowfall in winter or extreme drought in summer, the climate change in 1 month might affect the vegetation growth in the next month. The study found that the monthly average temperature, precipitation, and solar radiation

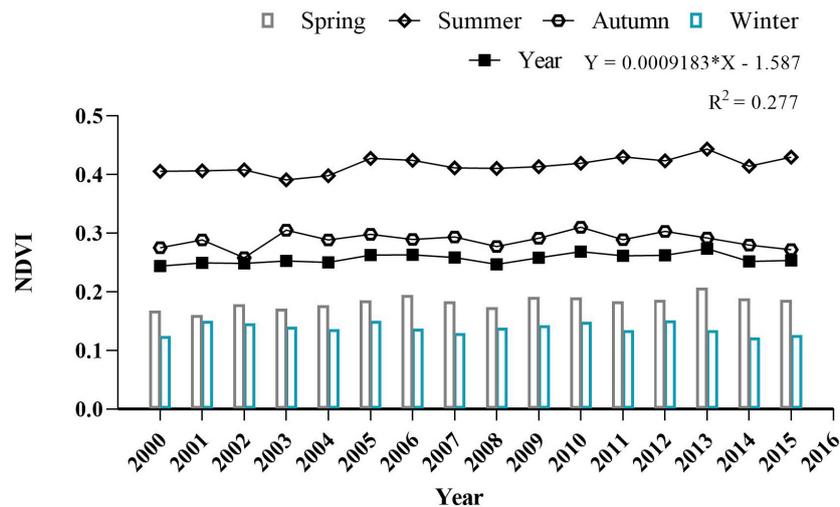


FIGURE 4

The change trend of normalized difference vegetation index (NDVI) of alpine wetland vegetation from 2000 to 2015.

of the wetlands in the TP from 2000 to 2015 were correlated with the monthly NDVI, and the results are shown in [Table 2](#).

As seen in [Table 2](#), the NDVI of alpine wetland vegetation in the TP was more influenced by the temperature factor, with the highest correlation coefficient of 0.686 ($P < 0.01$). The temperature of the current month and the temperature of the previous month were both strongly correlated with the NDVI of the growing season month. For correlation coefficients ranging from 0.6 to 0.8, it indicated that the recent temperature factor of the vegetation growing season positively influenced the NDVI. And from [Figure 6](#), we can get that the value of the real NDVI was higher than the value of linear regression when the temperature of the month before the growing season is higher than 10°C or lower than 8°C.

In contrast to the temperature factor which was greatly affected by the current month, the effect of solar radiation on vegetation was greater as time goes forward. The effect of solar radiation on NDVI was greater in the third month ahead than in the other times, reaching 0.636 ($P < 0.01$), which was a positive correlation ([Figure 6C](#)). The effect of solar radiation on NDVI was weaker or even uncorrelated at other times.

Precipitation in the month prior to the growing season had a greater effect on NDVI than precipitation in the current month, but the influence was not as strong as temperature and solar radiation, reaching only 0.574 ($P < 0.01$), which is a moderate correlation. This is consistent with [Wang et al.'s \(2011\)](#) study, where the correlation of mean temperature influenced the variation of NDVI on a long time scale. It can be seen from the relationship between NDVI in the growing season and the precipitation of the previous month ([Figure 6B](#)) that the higher the precipitation, the better the vegetation growth.

The relationship between precipitation, temperature, solar radiation factors, and wetland NDVI on the TP shows that all three climatic factors have a positive effect on NDVI, and there is a degree of lag between vegetation growth and changes in the climatic environment. The tipping points in vegetation NDVI between 2013 and 2014 may be due to abnormal weather in the first few months of the vegetation growing season.

3.4. Analysis of the impact of human activities on NDVI

Residual analysis calculated the trend of human activities by the difference between the real NDVI and the regression-predicted NDVI. [Figure 7](#) plots the distribution of the residuals sorted by time. The statistical results demonstrate that there is an unclear positive trend. Before 2008, the residuals were mostly negative, indicating that human activities might have a negative impact on vegetation. Conversely, human activities gradually had a positive impact on vegetation after this period, but this impact was relatively minor. In general, the anthropogenic influence showed a continuing positive trend, while the wetland vegetation on the TP might still be mainly influenced by climate.

4. Discussion

4.1. Responses of vegetation to climate

It was found that the annual mean NDVI increased from 2000 to 2015, and the mean NDVI in spring, summer and autumn also showed an increasing trend ([Figure 4](#)). The annual average temperature increased, precipitation decreased, and solar radiation increased ([Table 1](#)). Based on the analysis, the ecological environment of the TP developed toward a favorable direction under the positive impact of climate change, which is in accordance with the previous study ([Wang and Han, 2012](#)).

Surprisingly, we found that various scholars had different findings about the trend of precipitation on the TP. Some scholars found that the average annual precipitation had a decreasing trend ([Wang and Han, 2012](#); [Zhang et al., 2016](#); [Tang et al., 2018](#); [Zhe and Zhang, 2021](#)) while others believed that the TP was showing warm and humid development ([Sun and Qin, 2016](#); [Shen et al., 2022](#)). There may be three possible reasons for this phenomenon: (1) Spatial differences. The whole TP was warm and humid overall ([Sun and Qin, 2016](#)), but there were rainfall differences in different

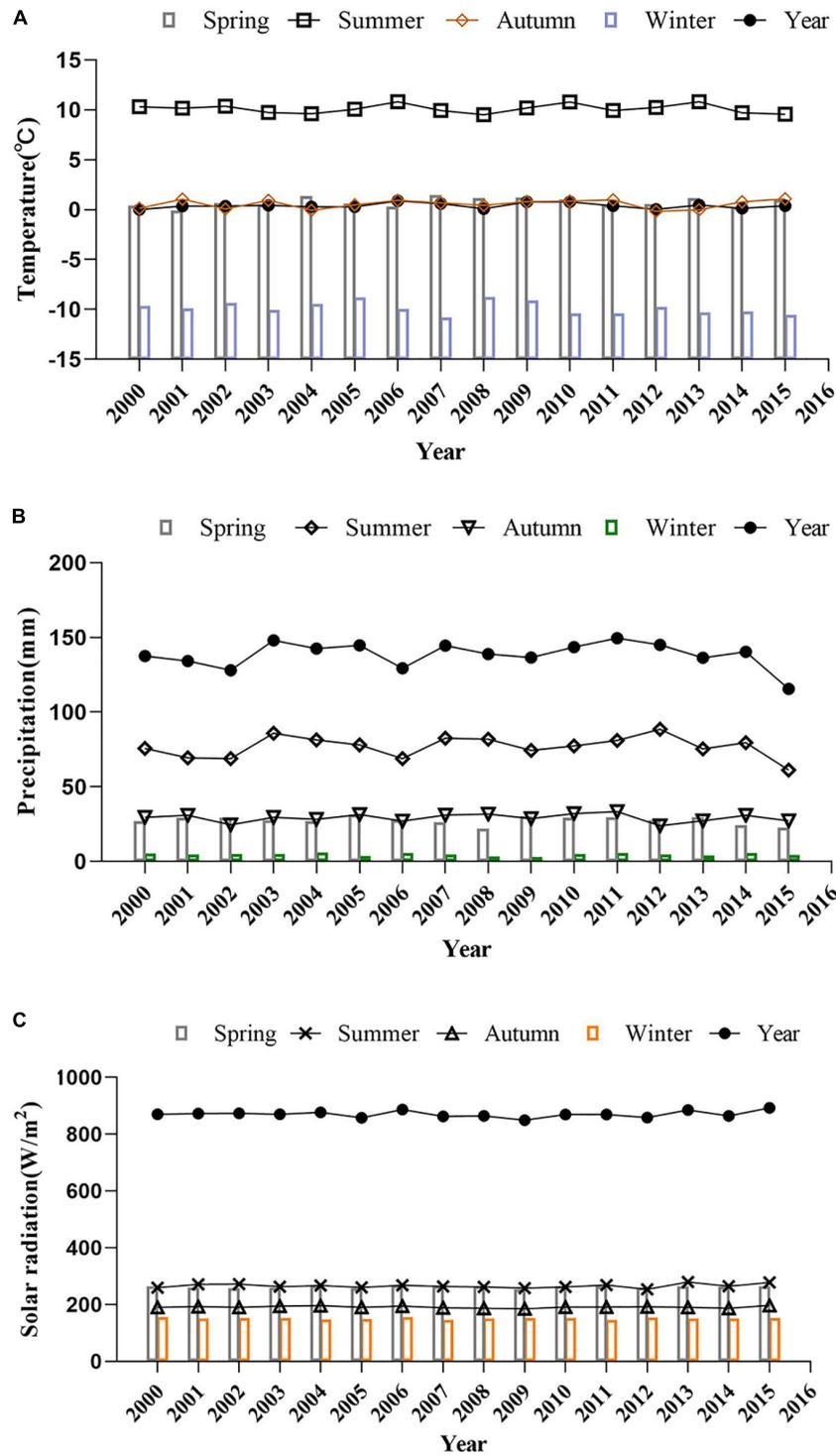


FIGURE 5 The change trend of (A) temperature, (B) precipitation, and (C) solar radiation from 2000 to 2015.

regions. (2) Temporal differences. Some scholars revealed a decline in precipitation by 2008 (Wang and Han, 2012; Zhang et al., 2016), while others found an increase by 2020 (Shen et al., 2022). (3) Vegetation species differences. Different types of vegetation may produce different sensitivities to climatic change. For example, from 2000 to 2017, the growing season precipitation of herbaceous marshes and seasonal brackish marshes on the TP showed an overall upward trend, while marshy meadows and inland salt marshes had a

downward trend (Kun et al., 2020). Therefore, the present study area is the wetland area of the TP with a trend of dry heat development from 2000 to 2015.

Mutations may be associated with phenology, long term changes and a “remainder” component related to irregular short-term variations or noise (e.g., clouds or atmospheric scatter) (Lambert et al., 2015). The annual as well as the spring, the summer average NDVI reached the highest value within 16 years in 2013 (Figure 4).

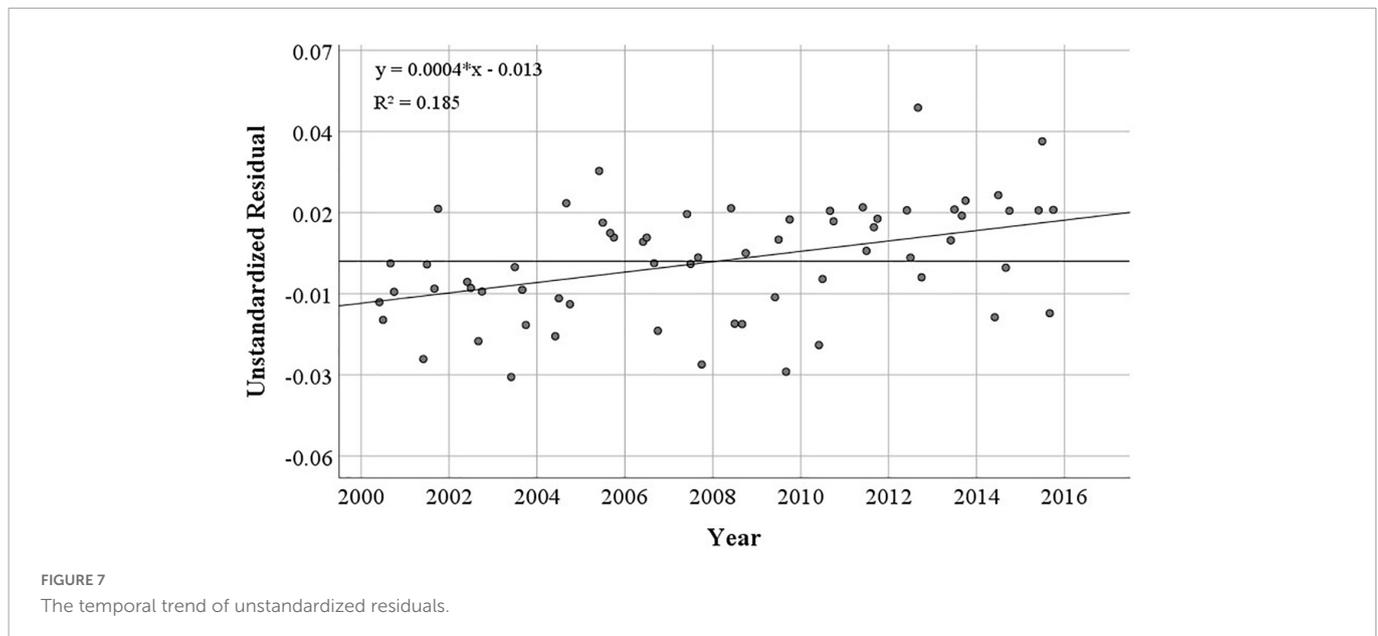
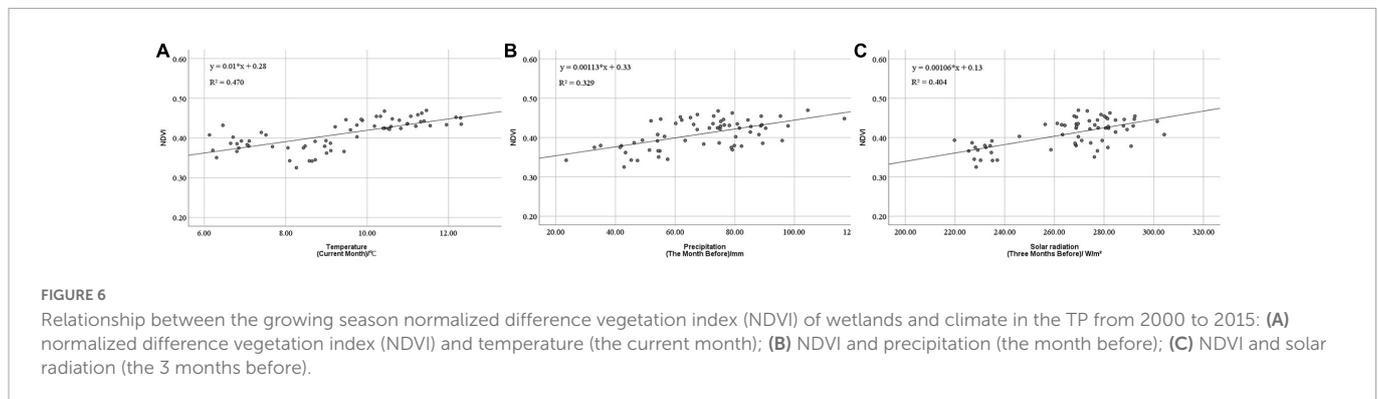
TABLE 1 The climate tendency rate statistical results of climate factor from 2000 to 2015.

Time scale	Temperature		Precipitation		Solar radiation	
	Linear equation	R	Linear equation	R	Linear equation	R
Spring	$y = 0.027 \times x - 52.94$	0.28	$y = -0.167 \times x + 362.2$	0.30	$y = 0.151 \times x - 42.12$	0.19
Summer	$y = -0.005 \times x + 20.79$	0.06	$y = 0.027 \times x + 22.58$	0.02	$y = 0.242 \times x - 220.9$	0.17
Autumn	$y = 0.013 \times x - 24.97$	0.14	$y = -0.014 \times x + 57.08$	0.02	$y = -0.068 \times x + 327.6$	0.10
Winter	$y = -0.052 \times x + 95.10$	0.40	$y = -0.030 \times x + 64.72$	0.16	$y = -0.099 \times x + 350.3$	0.15
Year	$y = 0.004 \times x - 8.011$	0.07	$y = -0.183 \times x + 506.6$	0.10	$y = 0.227 \times x + 414.8$	0.10

TABLE 2 Lag analysis of climate factors in different months on normalized difference vegetation index (NDVI).

	Correlation coefficient			
	Current month	The month before	Two months before	Three months before
Temperature	0.686**	0.610**	0.274*	0.246
Precipitation	0.326**	0.574**	0.306*	0.003
Solar radiation	0.138	-0.054	0.286*	0.636**

Significant at ** $P < 0.01$ and * $P < 0.05$ levels.



The tipping point of NDVI was at this time. In 2013, the temperature was at a high value at the corresponding time and the vegetation growth was good due to the positive correlation between temperature and vegetation growth. The precipitation in spring was also at a

high value, providing a good base for vegetation growth. The average monthly solar radiation in spring reached the second highest value within 15 years (264.77 W/m^2) and the highest value in summer (279.34 W/m^2). Adequate light ensured lush vegetation growth. In

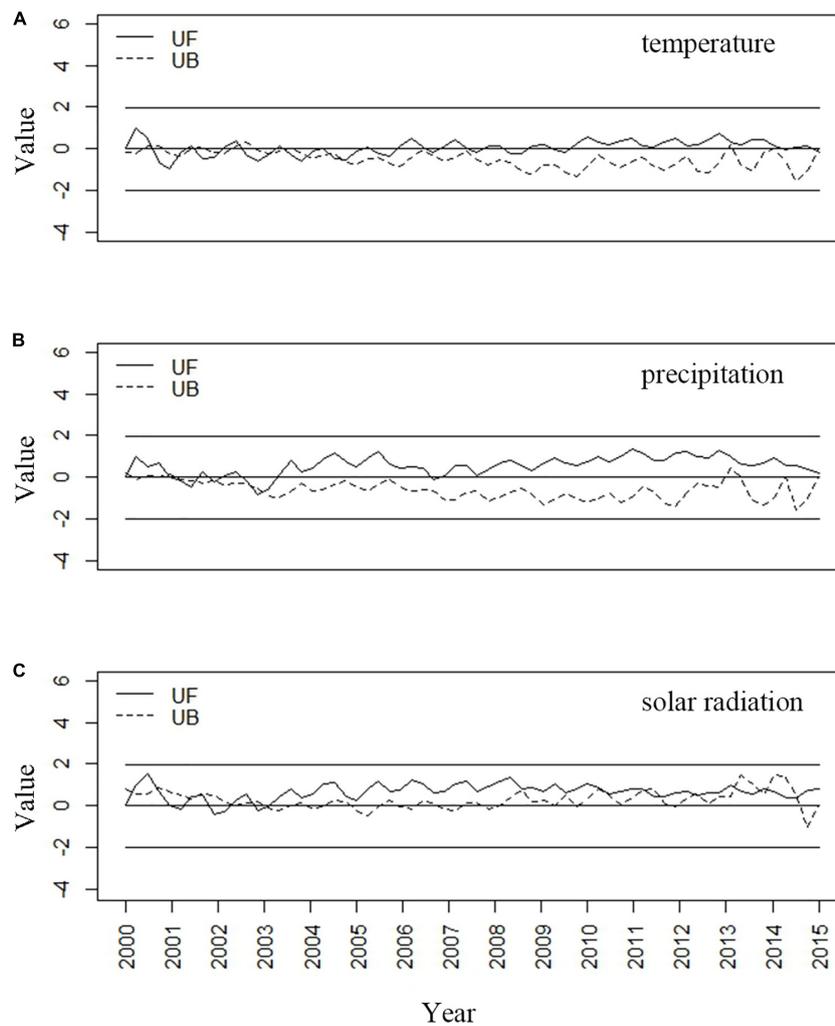


FIGURE 8

Mann–Kendall statistic curve of climate in vegetation growing season: (A) temperature (the current month); (B) precipitation (the month before); (C) solar radiation (the 3 months before).

the following 2 years, the precipitation and temperature decreased to a certain extent (Figures 5A, B), which may also lead to the vegetation growth being worse than that in 2013. Therefore, in BFAST detection, NDVI after 2013 has a downward trend.

The results of Mann–Kendall mutation test (Figure 8) showed that the changes in vegetation were approximately in line with the changes in meteorology. All three meteorological statistics had changes in 2013 (abrupt changes occurred when the UF and UB curves intersected). Among them, temperature and precipitation showed an increasing trend after a period of stability, with a trend of change after 2013, which was able to verify the abrupt change point of vegetation in 2013. For solar radiation, the UF and UB curves clearly intersected after 2013. Thus, the vegetation growth status changed equally when meteorological changes occurred, further proving that vegetation responds to climate.

4.2. Effect on vegetation greenness

The time lag effects of the vegetation responses to climates (Table 2) show significantly different lag effects of vegetation

responses to different climatic factors. Consequently, there was a significant correlation ($P < 0.01$) between the temperature and the growing season NDVI of the wetland. The inapparent time lag effect of air temperature may be due to a fact: it is a natural law that air temperature varies seasonally. During the plant growing season, air temperature is a key trigger for certain vegetation growth periods, and vegetation follows the change of air temperature into different growth periods (Duo et al., 2017). Thus, there is an inconspicuous time lag effect of air temperature on plant growth at the monthly scale. At the same time, we found that NDVI of wetland on the TP was more sensitive to temperature, which is consistent with the findings of Shen et al. (2014), Sun and Qin (2016), and Wang et al. (2020). Without water shortage, the temperature was the primary factor limiting vegetation growth, and the influence of precipitation on vegetation growth was less important.

Precipitation and solar radiation have a time-lag effect on NDVI. The time lag of the vegetation responses to precipitation in wetlands is approximately 1 month. In line with the findings of Zhe and Zhang (2021), NDVI values were most correlated with the cumulative climate values of the current and previous months. The difference is that we found that the precipitation of the previous month has a

higher correlation with NDVI. For solar radiation, the more forward the time is, the higher the correlation is. The time lag to solar radiation is 3 months which matches the observed in earlier studies (Wu et al., 2015). Possibly because the solar radiation in spring and summer is relatively consistent, so compared with other regions, vegetation on the TP is exposed to sufficient solar radiation earlier for photosynthesis.

The NDVI of wetland vegetation on the TP shows an overall upward trend, indicating that the vegetation is growing more luxuriantly. The major climate-driven factors for vegetation growth are diverse and are closely related to vegetation characteristics and climatic conditions. For the wetland areas of the Tibetan Plateau, the temperature is the primary factor that drives vegetation growth. Within a certain temperature range, the higher the temperature, the better the vegetation growth condition. Higher temperatures and more rain can promote photosynthesis, maintaining the role of wetlands as carbon sinks (Salimi et al., 2021). It should be noted that enhanced evapotranspiration and permafrost degradation might create an imbalance in soil temperature, moisture, and nutrients, limiting the growth of alpine vegetation (Yi et al., 2014; Wang et al., 2016).

Meanwhile, The result of NDVI residual (Figure 7) indicates that human activities have little positive impact. This study confirms that the TP is relatively undisturbed by human activities (Li et al., 2022). Wetlands were degraded and reduced in size from 1967 to 2004 (Zhang et al., 2011), however, they have since grown in size, which may be caused by human activities. In terms of vegetation growth, we believe that it is mainly affected by climate.

Overall, this study provides a theoretical basis for revealing the time-lag effects of alpine wetland vegetation responses to climate, and the results hold significant value for the climate-based prediction of variations in vegetation growth in the future.

4.3. Limitations and future work

The current study in this paper may have certain uncertainties and shortcomings. Firstly, the remote sensing data used in this study may be affected by clouds, atmosphere, solar altitude angle, and other factors, so the uncertainty of the data itself may affect the research results of this paper. Secondly, the climate of the TP is complex. It is a debatable issue whether the wetlands on the TP are developing warm and humid or dry and hot. Our next plan anticipates expanding the study time to discuss climate change over a longer time scale. In addition, wetland vegetation species are diverse and the growth periods are not identical, and the meteorological effects on different wetland vegetation need to be further revealed. In order to more accurately reveal wetland vegetation changes and their mechanisms on the TP, future studies need to be further supported by more precise data and research methods.

5. Conclusion

Taking alpine wetlands in the TP as an example, this research used mutation detection, correlation analysis and residual analysis to study the relationship between climate change, human activities and vegetation. The conclusion are divided into four specific sections.

- (1) The NDVI of wetlands on the TP showed a slight upward trend from 2000 to 2015, indicating an increase in vegetation greenness. The abrupt change in NDVI occurred between 2013 and 2014, and the NDVI values increased before the abrupt change and decreased after the abrupt change.
- (2) Temperature (0.04°C/10a) and solar radiation (2.27 W/m²/10a) increased and precipitation (−1.83 mm/10a) decreased, which means the wetlands of the TP showed a trend of dry-heating. Climate change varies widely from season to season.
- (3) NDVI of alpine wetland vegetation on the TP was strongly influenced by temperature factors. Precipitation in the first month before and solar radiation in the 3 months before were higher correlated with the NDVI of the vegetation growing season, reflecting the time-lag effect.
- (4) NDVI residual values were both positive and negative, with an overall slight upward trend with time. Human activities may have little positive impact on wetland vegetation in the TP.

Data availability statement

Publicly available datasets were analyzed in this study. This data can be found here: <http://www.resdc.cn> and <http://data.tpdc.ac.cn/zh-hans/>.

Author contributions

YC and JW: conceptualization. YC, LS, and JX: methodology, formal analysis, and investigation. YC and JX: software. YC: validation, data curation, writing—original draft preparation, and visualization. YC and LS: resources. BL, LS, and JW: writing—review and editing. JW, BL, and NX: supervision. JW: project administration and funding acquisition. All authors have read and agreed to the published version of the manuscript.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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