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ORIGINAL PAPER

NDVI-based vegetation responses to climate change in an arid area of China

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Abstract Warming of the climate system is unequivocal, and the change of climate variables will eventually have a great impact on vegetation cover and agricultural practices, especially in the arid area Xinjiang in China, whose agriculture and ecosystems are heavily vulnerable to climate change. In this paper, normalized difference vegetation index (NDVI) was used to study the vegetation growth and its response to climate change in Xinjiang. Firstly, two NDVI datasets (Global Inventory Modeling and Mapping Studies (GIMMS) and Moderate Resolution Imaging Spectroradiometer (MODIS)) were merged through a pixel-wise regression analysis to obtain a long time series of NDVI data, and then, relationships between yearly NDVI and yearly climate variables, and monthly NDVI and monthly climate variables were extensively investigated for grassland and cropland in northern and southern Xinjiang, respectively. Results show the following: (1) there was an increasing trend in NDVI for both grassland and cropland in both northern and southern Xinjiang over the past decades and trends were significant except that for grassland in northern Xinjiang; (2) precipitation and evaporation were more important than temperature for grassland in northern Xinjiang, while precipitation and temperature were more important than evaporation for grassland in southern Xinjiang and cropland in both northern and southern Xinjiang; (3) NDVI was highly correlated with accumulated monthly precipitation instead of monthly precipitation, and there was a lagged effect of precipitation, temperature, and evaporation on NDVI change. However, lagged effects were only significant in specific months. The results could be helpful to agricultural practices; e.g., based on lagged effect of precipitation, irrigation in July is very important for crop growth.

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1 Introduction

IPCC (2013) states "Warming of the climate system is unequivocal," and the change of climate variables (e.g., precipitation and temperature) will eventually have a great impact on vegetation cover and agricultural practices. The study of vegetation response to climate change has gain extensive attention in the past two decades (e.g., Piao et al. 2003; Yang et al. 2012). In the literature, normalized difference vegetation index (NDVI) has been frequently used as a reliable index to monitor the ground vegetation cover (e.g., Olusegun et al. 2013) and vegetation variability (e.g., Myneni et al. 1997; Schmidt et al. 2014) and study vegetation response to climate changes at regional, continental, and global scales over the past two decades (e.g., Kelly et al. 2008; Peng et al. 2012).

In arid regions, plant growth is water limited due to low precipitation while relatively high evapotranspiration and is highly sensitive to global climate change (McGwire et al. 2000; Fensholt et al. 2009). It is important to detect vegetation signals comprehensively and correctly such as vegetation coverage, biomass, and phenology in these areas (Wang et al. 2014). Detecting the dynamics of vegetation coverage and studying its relationship with climate variables are essential to assess the quality of ecosystem and maintain optimal ecosystem functioning (Mu et al. 2013).

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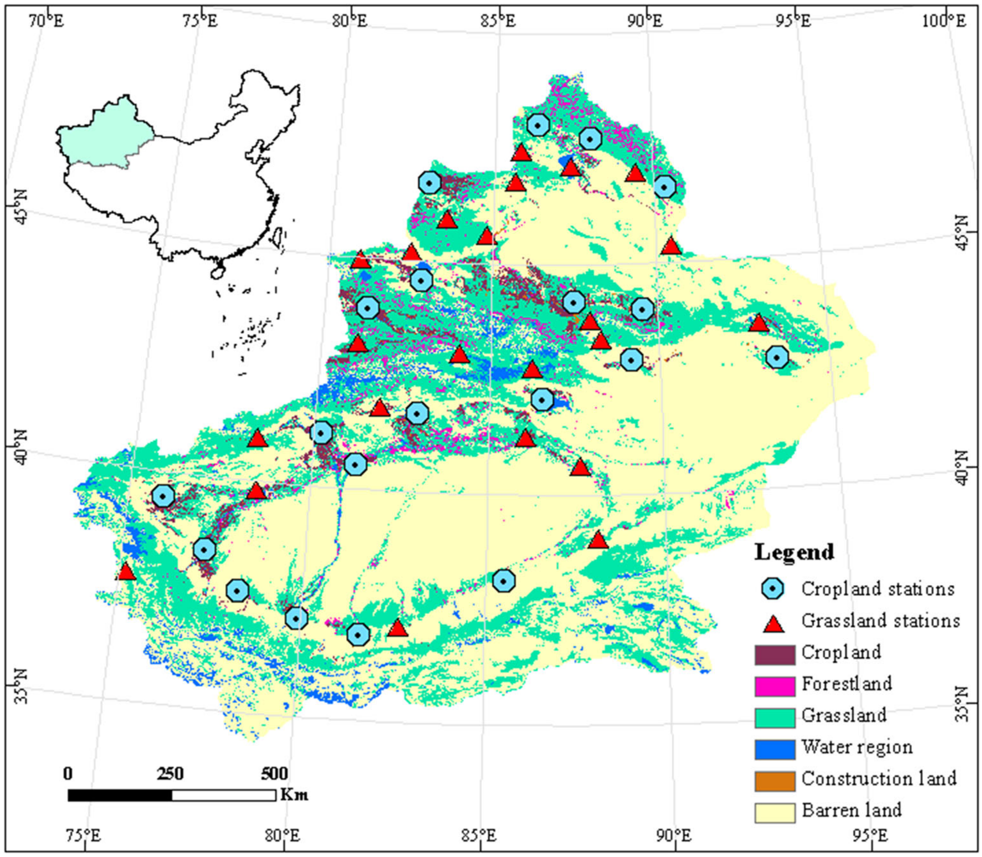
Fig. 1 The study area, land use types, and meteorological stations



Xinjiang (short for Xinjiang Uyghur Autonomous Region), a province in China (Fig. 1), lies in the arid area with low precipitation (about 150 mm/year) but high potential evapotranspiration (about 1100 mm/year) (Pu et al. 2011). Its economy depends on agriculture practices (i.e., grazing, crop, and orchard), and agriculture consumes over 90 % of total water use (Statistical Bureau of Xinjiang Uygur Autonomous Region 2010). Increasing trends of annual average temperature and precipitation have been observed in Xinjiang (Shi et al. 2007) with unprecedented global warming since 1980s. Study on the relationship between vegetation cover and climate will support the decision making on future adaption of agricultural practices to climate change in this region.

Although many researchers have paid attention to the variation of vegetation coverage and its relationship with climate variables in this area (e.g., Zhao et al. 2011; Cao et al. 2011; Zhang et al. 2009; Wang et al. 2013), results are quite different and some even contradict with each other. For example, Li (2000) and Li et al. (2009) show that NDVI is significantly correlated with both precipitation (*P*) and temperature (*T*), while Zhao et al. (2011) and Cao et al. (2011) show that NDVI change is highly correlated with *P* but not associated with temperature, and Guo et al. (2008) show that the correlation between NDVI and *T* is higher than that between NDVI and *P*. As most studies were based on regional averages and short periods of NDVI data (i.e., Global Inventory Modeling and Mapping Studies (GIMMS) data which are available only to 2006 as Moderate Resolution Imaging Spectroradiometer (MODIS) NDVI starts from 2001) and spatially extrapolated/interpolated precipitation and temperature, there is a need to study if longer data provides any different relationship between NDVI and precipitation and temperature, how vegetation types in different regions respond to climate variables other than precipitation and temperature, and how different it would be if station based instead of extrapolated/interpolated climate data were used. In this paper, we addressed these issues by studying the responses of grassland and cropland to climate variables (precipitation, accumulated precipitation, mean temperature, minimum temperature, maximum temperature, and evaporation) at a yearly and a monthly scales in northern and southern Xinjiang, respectively, with prolonged time series of NDVI data by combining two difference sources (i.e., GIMMS and MODIS).

2 Data and methods

2.1 Study area

Xinjiang (Fig. 1), with an area of more than 1.66 million km^2, is located in the geographic center of Eurasia, extending from 73° 32′ E to 96° 21′ E and from 34° 22′ N to 49° 33′ N. It is divided into two large basins by the Tianshan Mountain Range: the northern Xinjiang and the southern Xinjiang. The northern Xinjiang is dominated by the Gurbantünggüt Desert, which is the third largest fixed and semi-fixed desert in the world, with the annual mean temperature varying from 3 to 7.5 °C and annual precipitation from 150 to 200 mm. The southern Xinjiang is dominated by the Taklamakan Desert, which is the second largest shifting sand desert in the world, with the annual mean temperature varying from 9 to 12 °C and annual precipitation less than 200 mm in the north and less than 85 mm in the south with a strong spatial heterogeneity. The vegetation in Xinjiang is mainly distributed in the mountainous areas and oases, and surface runoff is generated in the mountains, flows through the Oasis, and finally disappears in the desert.

2.2 NDVI data and land use map

The NDVI datasets used in this study are GIMMS NDVI and MODIS NDVI. Both datasets have been widely applied in large-scale studies of vegetation activity recently (Slayback et al. 2003; Badreldin et al. 2014). GIMMS NDVI data available from 1982 to 2006 were obtained from the West Data Center of China (http://westdc.westgis.ac.cn/about/terms), at a spatial resolution of 8 km and a temporal resolution of 15 days, while MODIS NDVI data from 2001 to 2013 were obtained from NASA's Earth Observing System, at a resolution of 1 km and a temporal resolution of 1 month. For GIMMS NDVI, to minimize the effects of atmospheric and aerosol scattering, monthly NDVI data were produced by using the maximum value composite (Holben 1986) method, and cells with monthly NDVI values less than 0.1 were excluded to reduce the influence of deserts, sparsely vegetated areas, and snow. The growing season was defined as from May to October, and the yearly NDVI data were obtained by averaging monthly NDVI data over the growing season for each year.

Digital land use map, digitized from the land use map in year 2000 with a scale 1:100,000, was also provided by West Data Center of China, at a spatial resolution of 1 km. Figure 1 shows the spatial distribution of vegetation types in Xinjiang.

2.3 Climate data

Daily climatic data of 53 climatic stations across Xinjiang (Fig. 1), collected from the National Meteorological Center of China, include daily precipitation (P), minimum temperature ($T_{\min}$), maximum temperature ($T_{\max}$), and mean temperature (T_{mean}) from 1982 to 2013. Monthly climate data and yearly climate data were then aggregated based on daily data. Additionally, the accumulated monthly precipitation (AP) and the potential evapotranspiration (PET) were used in this study. PET, used to quantify the degree of dry condition, was calculated using the Penman-Monteith equation suggested by Food and Agriculture Organization (Allen et al. 1998):

$$PET = \frac{0.408\delta(R_n - G) + \gamma\left(900 \big/ (T+273)\right)U_2(e_s - e_a)}{\delta + \gamma(1+0.34U_2)} \quad (1)$$

where δ is the slope of vapor pressure curve (kP$_a$ °C^{-1}),R$_n$ is the net solar radiation at the plant surface (MJm^{-2} day^{-1}), G is the soil heat flux density (MJm^{-2} day^{-1}), γ is the psychrometric constant (kP$_a$ °C^{-1}), T is the mean air temperature at a height of 2 m (°C), U_2 is the mean wind speed at a height of 2 m (ms^{-1}), e_s is the saturation vapor pressure (kP$_a$), and e_a is the actual vapor pressure (kP$_a$). PET was calculated based on the R package "SPEI" (http://cran.r-project.org/web/packages/SPEI/index.html; Vicente-Serrano et al. 2010) by providing observed atmospheric pressure, wind speed, relative humidity, $T_{\min}$, $T_{\max}$, bright sunshine hours, and latitude and elevation of the given station.

2.4 Methods

2.4.1 Extension of time series of NDVI

Since GIMMS NDVI data span a longer period of time (from 1982 to 2006) than MODIS NDVI data, MODIS NDVI data were used to extend GIMMS NDVI data to the period from 2006 to 2013 based on the following steps: firstly, monthly MODIS NDVI data were resampled from 1- to 8-km resolution to match the resolution of monthly GIMMS NDVI data, and then, a pixel-wise linear regression was done between monthly GIMMS NDVI data and resampled monthly MODIS NDVI data for the period of 2001 to 2006 when these two datasets overlap; finally, the linear regression was used to extend monthly GIMMS NDVI data from 2007 to 2013. Pixel-wise regression analysis has been applied to integrate different sensor data and obtained reasonable good results (Mao et al. 2012; Xin et al. 2008).

To study vegetation response to climatic change, the continuity and consistency of these two NDVI datasets are essential (Steven et al. 2003). To check the accuracy of the extended NDVI series, we performed statistical analyses (i.e., R^2 and root-mean-square error (RMSE)) on GIMMS NDVI and modeled NDVI through regression analysis for the period from 2001 to 2006.

2.4.2 Relationship between NDVI data and climate variables

Climate stations are very sparse in the Xinjiang region (i.e., ~180,000 km^2/station), and most stations are located in cropland (21 stations) and grassland (26 stations). Therefore, this study is only limited to cropland and grassland areas. To guarantee the accuracy, monthly NDVI data for analysis were extracted for grassland and cropland pixels within a 10-km buffer of each weather station (Ji and Peters 2004). Yearly, NDVI values were averaged over the monthly NDVI values for the growing season (from May to October). These NDVI data and climate data were then summarized into four groups, i.e., grassland in northern Xinjiang, grassland in southern Xinjiang, cropland in northern Xinjiang, and cropland in southern Xinjiang.

Long-term trends were analyzed for yearly NDVI, yearly climate variables, monthly NDVI, and monthly climate variables. Then, correlation analysis was also used to illustrate the relationship between NDVI and climate variables for cropland and grassland, respectively. As there might be a lag between NDVIs to climate variables, correlation analysis was also applied to lagged NDVI and climate variables.

3 Results

3.1 Extension of GIMMS NDVI data

After the pixel-wise regression analysis, the performance of the regression analysis was evaluated at pixels around meteorological stations and in the entire study area, by comparing GIMMS NDVI, modeled NDVI (i.e., through regression analysis), and MODIS NDVI for the period from 2001 to 2006. For pixels around meteorological stations (Fig. 2a), compared to monthly MODIS NDVI (gray points), monthly modeled NDVIs (black points) are closer to the 1:1 line (black line) with R^2 0.93 and RMSE is around half of that of MODIS NDVI, which indicates a good match between GIMMS NDVI and modeled NDVI. Similar good performance was also obtained in the entire study area (Fig. 2b) with R^2 0.98 and RMSE half of that for MODIS NDVI. These results mean that the pixel-wise regression can be used to extend the GIMMS NDVI data from 2007 to 2013, which will be used to study the relationship between vegetation cover and climate variables.

3.2 Yearly NDVI and its response to climate change

Figure 3 shows interannual variations of climate variables (P, T_{mean}, and PET) and yearly NDVI for grassland and cropland in northern and southern Xinjiang from 1982 to 2013.

Yearly average precipitation amounts in grassland were similar in northern Xinjiang and southern Xinjiang, while, in cropland, they were higher in northern Xinjiang than in southern Xinjiang. All P time series experienced an increase while it was only significant in grassland in southern Xinjiang. T_{mean} in grassland was higher in the north than in the south while the converse is true for T_{mean} in cropland, and all T_{mean} time series had a significantly increasing trend especially in grassland in southern Xinjiang. Yearly PET had a similar spatial and temporal pattern as yearly T_{mean} except that trends of PET were insignificant.

For grassland, generally, NDVI was slightly lower in northern Xinjiang than in southern Xinjiang while, for cropland, NDVI was much higher in northern Xinjiang than in southern Xinjiang. There was a significantly increasing annual trend for grassland in southern Xinjiang and cropland in both northern and southern Xinjiang, while the increase for grassland in northern Xinjiang was insignificant, partly due to insignificant changes of climate variables in northern Xinjiang. NDVI in grassland increased more rapidly in southern Xinjiang (0.002 year^{-1}) than in northern Xinjiang (0.001 year^{-1}) while, that in cropland, increased at a similar speed (0.003 year^{-1}) in northern and southern Xinjiang.

Table 1 lists correlations between yearly climate variable and NDVI from 1982 to 2013. For grassland in northern Xinjiang, yearly NDVI had a significant positive correlation with P (R=0.72) and a significant negative correlation with PET (R=−0.62), while it did not show too much correlation

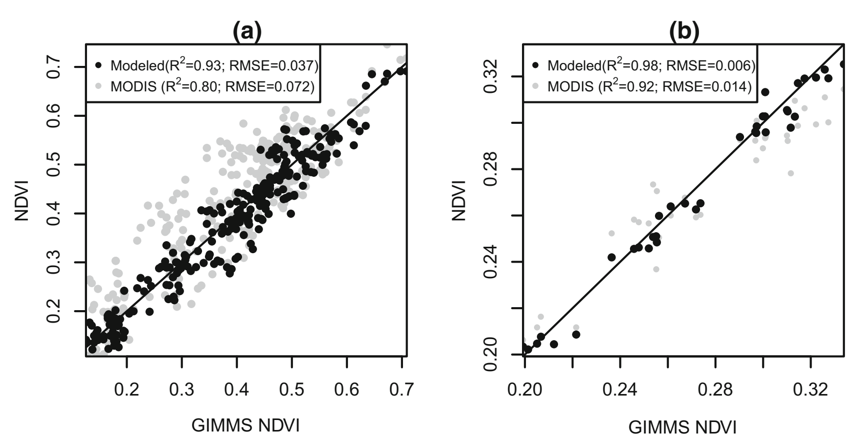


Fig. 2 Comparison of **a** yearly GIMMS NDVI, modeled NDVI, and MODIS NDVI at pixels around meteorological stations and **b** monthly GIMMS NDVI, modeled NDVI, and MODIS NDVI averaged over the study area during the growing season, from 2001 to 2006 (*black line*, 1:1 line; *black points*, modeled NDVI; *gray points*, MODIS NDVI)

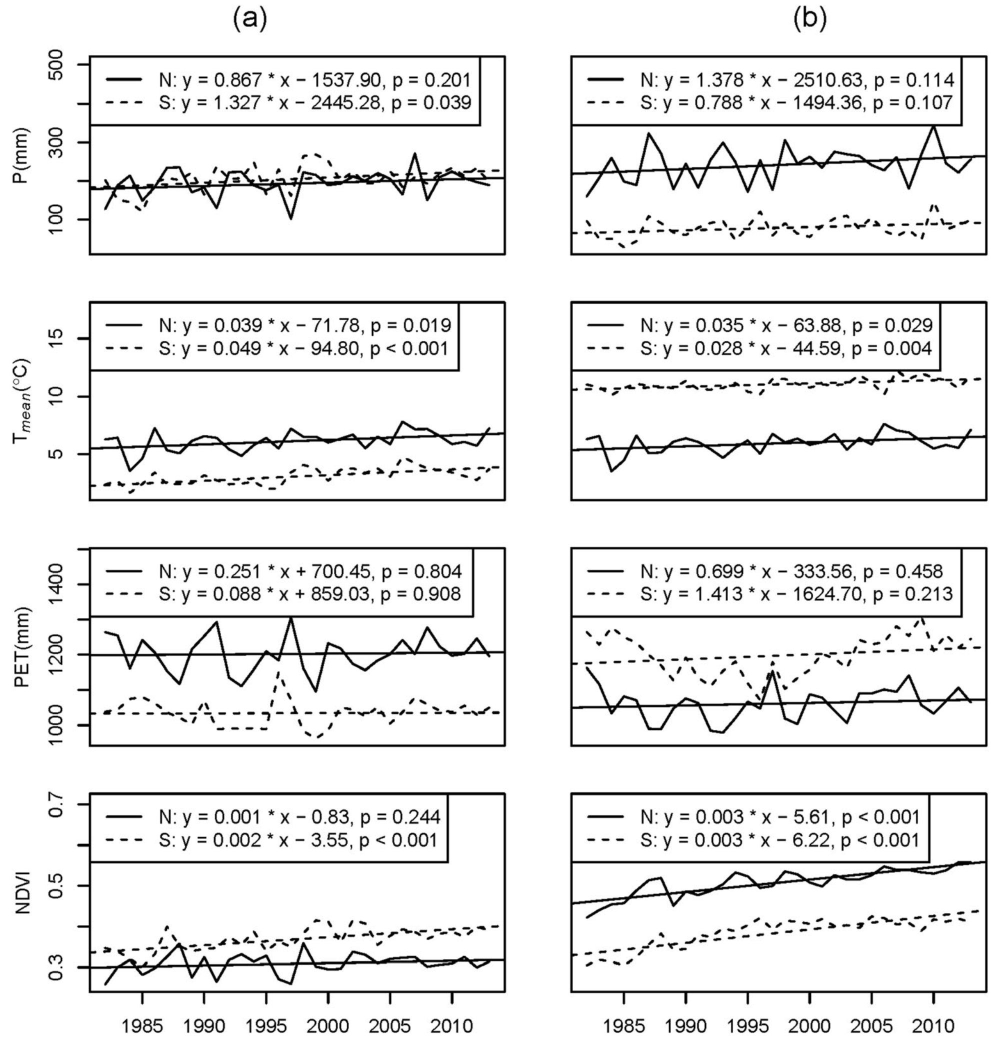


Fig. 3 Interannual variations of P, T_{mean}, PET, and NDVI for **a** grassland (*left*) and **b** cropland (*right*) from 1982 to 2013 (*N*: northern Xinjiang; *S*: southern Xinjiang)

with T (T_{min}, T_{mean}, and T_{max}); in southern Xinjiang, yearly NDVI had significant correlations with P (R=0.69) and T (0.47, 0.61, and 0.40 for T_{mean}, T_{min}, and T_{max}, respectively) while negative correlation with PET (R=−0.31). The huge difference in coefficients with temperatures in the south and in the north shows that grassland in the south was more sensitive to temperature change than in the north, which might be that grasslands in the south are distributed in higher elevations than in the north (average elevations are 2158 and 864 m for grasslands in the south and in the north, respectively). Compared to results based on data without extension (i.e., 1982~2006), changes were insignificant except correlation

Table 1 Correlation coefficients between yearly climate variables and yearly NDVI for grassland and cropland in southern Xinjiang and northern Xinjiang based on data from 1982 to 2013

Climate variable	Grassland		Cropland	
	Northern Xinjiang	Southern Xinjiang	Northern Xinjiang	Southern Xinjiang
P	0.72** (0.77**)	0.69** (0.69**)	0.42* (0.52**)	0.46* (0.49*)
T_{mean}	−0.12 (−0.16)	0.47** (0.46*)	0.31 (0.24)	0.24 (0.11)
T_{min}	0.07 (0.03)	0.61** (0.64**)	0.42* (0.33)	0.62** (0.61**)
T_{max}	−0.22 (−0.29)	0.40* (0.37)	0.27 (0.15)	0.39* (0.37)
PET	−0.62** (−0.64**)	−0.31 (−0.41*)	−0.16 (−0.38)	−0.25 (0.53**)

Numbers in the brackets are corresponding correlations based on data from 1982 to 2006

*Significant at level 0.05; **significant at level 0.01

between NDVI and PET in southern Xinjiang which was more significant with extended data.

For cropland, yearly NDVI in the north had a significant and positive correlation with P (R=0.42) and T_{min} (R=0.42), a positive correlation with T_{mean} and T_{max}, and negative and insignificant correlation with PET. Similar results can be obtained for cropland in southern Xinjiang, except that correlations between NDVI and T_{min} and T_{max} were more significant. Compared to the results for grassland, P and PET were less important. Compared to correlations based on data from 1982 to 2006 for cropland, the importance of P and PET decreased (especially, correlation between NDVI and PET decreased from a highly significant value −0.53 to an insignificant value −0.25 in southern Xinjiang), while that of temperature increased slightly.

3.3 Monthly NDVI and its response to climate change

Figure 4 shows mean monthly values (line) and trends (gray bars) of monthly climate variables (i.e., P, AP, T_{mean}, and PET) and NDVI during the growing season from 1982 to 2013. Figure 5 shows normal (i.e., with no lag) correlation coefficients (solid lines) and 1-month (dashed), 2-month (dotted), and 3-month lagged correlation coefficients.

3.3.1 Monthly trends of NDVI and climate variables

In grassland, mean monthly P values were more evenly distributed in northern Xinjiang (Fig. 4a) than in southern Xinjiang (Fig. 4b) which led to a steady increase of mean

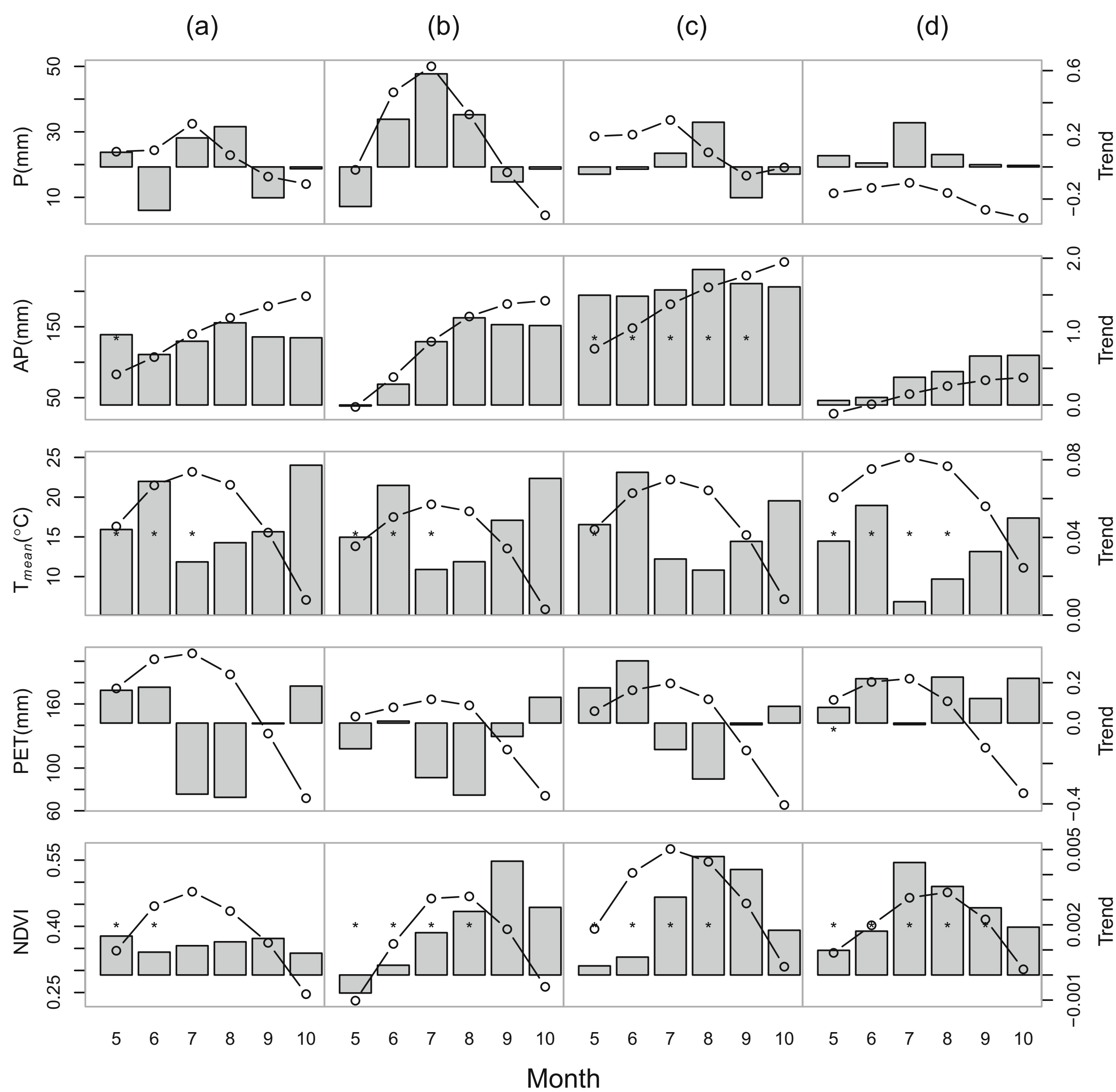


Fig. 4 Mean monthly values (*lines*) and trends (*bars*) of monthly climatic variables (P, AP, T_{mean}, and PET) and NDVI during the growing season for grassland in **a** northern Xinjiang and **b** southern Xinjiang and cropland in **c** northern Xinjiang and **d** southern Xinjiang (*significant at level 0.05)

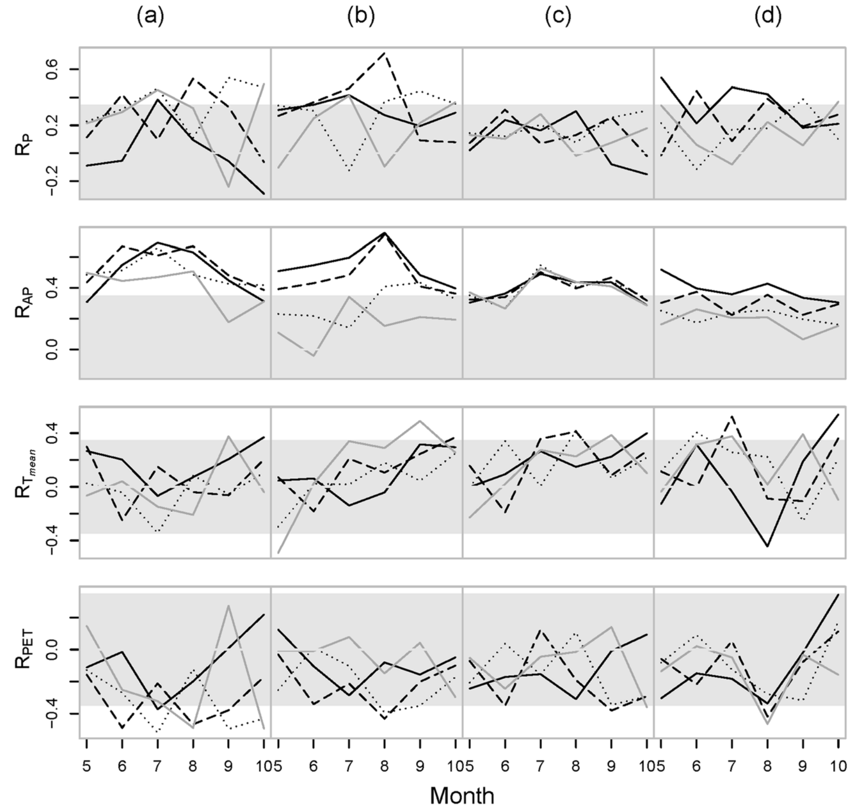


Fig. 5 Correlation coefficients between monthly NDVI (solid line: no lag; dashed line: 1-month lag; dotted line: 2-month lag; grey line: three-month lag) and climatic variables during the growing season for grassland in **a** northern Xinjiang and **b** southern Xinjiang and cropland in **c** northern Xinjiang and **d** southern Xinjiang (*shaded area* denotes insignificant area at level 0.05)

monthly AP in northern Xinjiang. Yearly trends of mean monthly *P* were insignificant, and the trends of mean monthly AP were lower in northern Xinjiang than in south Xinjiang. In both regions, mean monthly T_{mean} had a same monthly distribution pattern and similar increasing trends. Mean monthly PET has a similar pattern as mean monthly T_{mean}. Mean monthly NDVI had a similar pattern as monthly T_{mean} and PET, and increasing trends were observed in both regions (except the decrease trend in May in the south).

In cropland, monthly mean *P* values were higher in the north than in the south, so were monthly mean AP values. The trends of mean monthly *P* were small and insignificant in both regions while trends of mean monthly AP in northern Xinjiang were significant (except in October) and higher than those in southern Xinjiang. For T_{mean}, mean monthly values were slightly lower in northern Xinjiang than in southern Xinjiang, while monthly trends were very similar both regions. For mean monthly PET, its pattern was similar to that of T_{mean}, and its trend shape in northern Xinjiang was very similar to that in grassland in northern Xinjiang while those trends in southern Xinjiang were all increasing. Mean monthly NDVI had a similar pattern as T_{mean} and PET in a similar way in grassland, and their trends were significant from May to August. Mean monthly NDVI values of cropland were larger than those of grassland.

3.3.2 Response of monthly NDVI to monthly climate variables

For grassland, generally, normal and lagged correlations between NDVI and *P* were significant in some specific months, and lagged coefficients indicate that there was a time lag for precipitation to be used for grass development, i.e., a lagged water movement in the atmosphere-soil-plant continuum. Compared to normal correlations between NDVI and *P*, these between NDVI and AP were higher and more significant. These results suggest that AP instead of *P* had better correlations with grass growth, which is a reflection of lag and accumulative effects of *P* on vegetation during the growing season. Normal and lagged correlations between monthly NDVI and T_{mean} were not significant except some specific months. Monthly NDVI in the north was only significantly related to PET in July while their correlations in the south were not significant, and differently lagged coefficients were significant in some specific months, indicating that PET in the previous months can depress grass growth in current month through depleting the soil moisture in previous months.

For cropland, normal and lagged correlations between NDVI and *P* were generally higher in the south than in the north and they were only significant in some months in the south. For AP, normal correlations were positive and mostly significant. Lagged correlations were similar to those with no lag, and these in the south were decreasing and insignificant for 2- and 3-month lagged coefficients. For T_{mean}, normal correlations in both regions were insignificant except October in the north and August and October in the south. Lagged correlations were only significant in specific months. For PET, normal and lagged correlations were negative and only significant in some specific months.

4 Discussion

As shown in Sect. 3.2, all NDVI time series had an increasing trend, which is consistent with previous studies (e.g., Cao et al. 2011; Zhao et al. 2011; Zhang et al. 2009), and generally, NDVI had a positive correlation with *P* while a negative correlation with PET which implies that *P* was the key factor for vegetation growth while PET was the competing factor which generally reduces water availability (Piao et al. 2006; Li et al. 2002). There is a difference in relationships between NDVI and climate variables in grassland and in cropland: *P* and PET were less important in cropland than in grassland. This might be explained by increasing irrigation in croplands in the study area in the past decades. Therefore, *P* was a less stressing factor for crop growth. This indicates that human activity played a very important role in the NDVI change for cropland than grassland. Figure 6 shows time series of yearly NDVI and effective irrigation area (top) and the scatter plots between yearly NDVI and effective irrigation area (bottom). NDVI response is linear up to an area of around 2800×10^3 ha, and then, it saturates and NDVI is almost constant, irrespectively of changes in the area. This suggests that irrigation may have an impact at low areas but not at high areas. Irrigation could change the way *P* interacts with crop, as it can effectively change soil water conditions. As effective irrigation areas are only available at the provincial level, NDVI response cannot be examined for irrigation areas over 2800×10^3 ha.

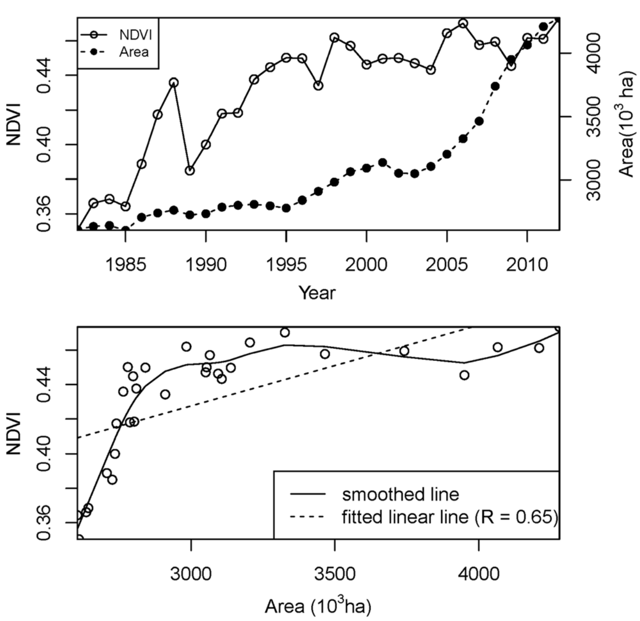


Fig. 6 Interannual variations (*top*) and scatter plot (*bottom*) of NDVI and effective irrigation area in cropland

In the literature, when the relationships between NDVI and climate variables were studied, treatments of NDVI and climate variables are different: the climate variables are first extrapolated/interpolated to the entire research area, and then, correlations are calculated either pixel based (Cao et al. 2011), region based (Li et al. 2009), vegetation type based (Zhang et al. 2009), or both region and vegetation type based (Zhao et al. 2011). This makes the comparison hard, and some results contradict each other (see Cao et al. 2011 for cases of contradiction). Here, we compared our results with those of similar regions and vegetation types in the literature. For our results, as far as regions are concerned, NDVI shows high correlations with *P* in both regions (0.72 and 0.42 in northern Xinjiang; and 0.69 and 0.46 in southern Xinjiang), but low correlations with T_{mean} in the north (−0.12 and 0.31 in northern Xinjiang) and high in the south (0.47 and 0.24) which are generally similar to Li et al. (2009) (i.e., correlations between NDVI and *P* are 0.716 and 0.829 in the north and in the south and between NDVI and T_{mean} are 0.483 and 0.753 in the north and in the south) with some differences in numbers; concerning vegetation types, correlations between NDVI and *P* are significant, and they are higher in grassland (0.72 and 0.69) than in cropland (0.42 and 0.46) which is generally similar to Zhang et al. (2009) (i.e., correlation between NDVI and *P* are 0.42~0.52 in grassland and 0.34 in cropland), and T_{mean} was only important in grassland (in the south 0.47) although there is an increasing importance on cropland. The differences above might be attributed to the way to treat the NDVI and climate data.

The lagged response of NDVI to climate change has been examined, and time lags vary spatially and temporally due to different region characteristics (topography, climate, soil, etc.) and crop type. Most studies indicate an up to 3-month lagged relationship (e.g., Richard and Poccard 1998; Piao et al. 2003; Wang et al. 2013; Piao et al. 2006; Guo et al. 2014). In our study region, Guo et al. (2014) show 1-month lag of NDVI response to both precipitation and temperature, and Cao et al. (2011) show an around 20-day lag. However, in our study, except AP, the lagged effects were only significant in some specific months (i.e., there was no general trend for all months), and it shows a huge difference for different regions and different vegetation types. This characteristic might be smoothed out through climate extrapolation/interpolation and NDVI regional average when using extrapolated/interpolated climate data and regional analysis in other studies. The lagged characteristic might be helpful for agricultural practices. For example, in Fig. 5d, *P* in July was positively and significantly correlated with NDVI in July (no lag), August (1-month lag), and September (2-month lag) for cropland in southern Xinjiang. This means that measures (e.g., irrigation) could be taken to help crop development in drought conditions.

5 Conclusions

In this paper, GIMMS NDVI data were extended from 2007 to 2013 through a pixel-wise regression analysis, and then, relationships between NDVI and climate variables were extensively studied at yearly and monthly scales in grassland and cropland in southern and northern Xinjiang. Yearly analysis shows that there was an increasing trend in NDVI for both grassland and cropland over the past decades, and these trends were significant except that for grassland in northern Xinjiang. For grassland, *P* and PET were more important than temperature to grass growth in northern Xinjiang, while *P* and temperature were more important than PET in southern Xinjiang. For cropland, *P* and temperature were important to crop growth while PET was not significant. Monthly analysis shows that NDVI was highly correlated with AP instead of *P*. There was a lagged effect of *P*, temperature, and PET on NDVI change for both grassland and cropland. This lagged effect varied differently for grassland and cropland in northern and southern Xinjiang and was only significant to climate variables in specific months.

Results also show that there is a difference in the relationship between NDVI and climate variables, especially for cropland, when compared results without data extension, which indicates the necessity to extend the data to obtain an update relationship. Furthermore, as discussed above, the importance of *P* was lower for cropland than for grassland. All these indicate the anthropogenic effect on vegetation development. Over the past three decades, due to human activity, land use has changed significantly in Xinjiang which has changed spatial and temporal distribution of water resources and hence changed the way that vegetation interacts with climate variables naturally. Therefore, it is important to study how vegetation interacts with climate and human activity, especially under future climate change, and to separate contributions from human activity and climate variables, which will be very beneficial to local economic development and ecosystem. This will be our next goal. However, the results obtained here could be very useful to agricultural practices. For example, as far as lagged coefficient concerned, *P* in July was positively and significantly correlated with NDVI in July (no lag), August (1-month lag), and September (2-month lag) for grassland and cropland. This means that measures (e.g., irrigation) could be taken to help vegetation development in drought conditions.

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