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Changing climate affects vegetation growth in the arid region of the northwestern China

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ABSTRACT

The northwestern China is a typical dry-land region of Inner Asia, where significant climate change has been observed over the past several decades. How the regional vegetation, particularly the grassland-oasis-desert complex, responds to such climatic change is poorly understood. To address this question, we investigated spatio-temporal changes in vegetation growth and their responses to a changing climate by biome and bioregion, using satellite-sensed Normalized Difference Vegetation Index (NDVI) data from 1982 to 2003, along with corresponding climate data. Over the past 22 years, about 30% of the total vegetated area showed an annual increase of 0.7% in growing season NDVI. This trend occurred in all biomes and all bioregions except Sawuer, a subregion of the study area with no significant climate change. Further analyses indicated that NDVI change was highly correlated with the current precipitation and evapotranspiration in growing season but was not associated with temperature. We also found that NDVI was positively correlated with the preceding winter precipitation. These findings suggest that precipitation may be the key cause of vegetation growth in this area, even for mountain forests and grasslands, whose growth are often regarded to be limited by low temperate in winter and early spring.

1. Introduction

Recent global climate change has already exerted significant impacts on terrestrial ecosystems and the impacts are projected to be greater in the future (IPCC, 2007; Walther et al., 2002). Many studies based on analyses of satellite images have detected a greening trend at global (Myneni et al., 1997; Nemani et al., 2003; Potter et al., 2007; Zhou et al., 2001) and regional scales (Donohue et al., 2009; Fang et al., 2004; Herrmann et al., 2005). However, the response of vegetation to climatic changes widely differed by biome (Fang et al., 2005; Piao et al., 2006) and bioregion (Verbyla, 2008).

The northwestern China is located in the inner center of Eurasia. Its core region, Xinjiang Uygur Autonomous Region, covers a terrain of 1,665,000 km^2 (about 3 times the size of France), and borders on eight nations in Asia: Mongolia and Russia in the north, Kazakhstan, Kyrgyzstan, Tajikistan, and Afghanistan in the west, and Pakistan and India in the south (Fig. 1). The landscape of the region is characterized by a unique morphological complexity consisting of mountains, basins and rivers, and therefore generates the region's diverse biomes (forests, grasslands, deserts and oases). Such geological and biotic complexity, together with well-documented ground-based information on climate and vegetation, have attracted a number of researchers (Fang et al., 2004; Jia et al., 2004; Ren et al., 2007; Shen, 2009). Previous studies have showed that climate in this region has shifted from a warm-dry to a warm-wet type (warm-dry to warm-wet transition) since the 1980s (Shi et al., 2002, 2007). In order to detect whether such a climatic transformation has led to an increase in plant growth at the biome and bioregion scale, we investigated the interannual changes in vegetation cover over the period of 1982–2003 using satellite-derived normalized difference vegetation index (NDVI) data set.

2. Data and methods

2.1. NDVI data

The time series data of NDVI used in this study were the third-generation data set from the Global Inventory Monitoring and Modeling Studies group using the Advanced Very High Resolution Radiometer (AVHRR) on board the National Oceanic and

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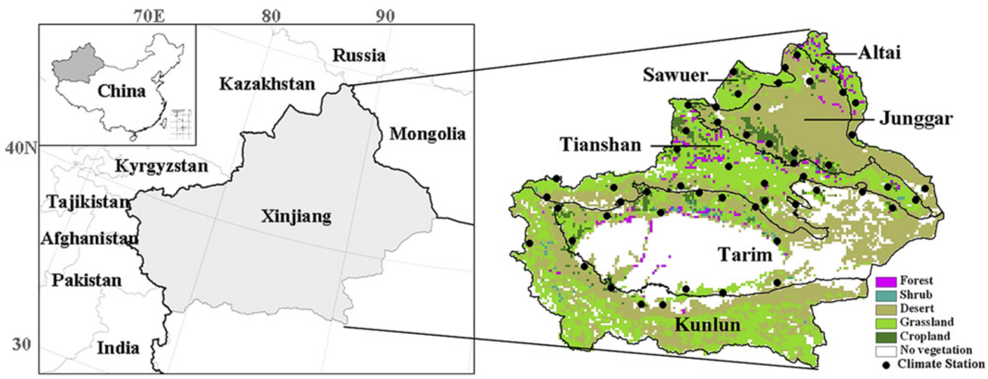

Fig. 1. Location of the research area and distribution of vegetation types and climate stations in the six bioregions in Xinjiang.

Atmospheric Administration satellites, at a spatial resolution of 8 × 8 km^2 with 15-day interval, for the period January 1982 to December 2003. A number of the previous studies have confirmed a reliable quality of this NDVI time series data set (Los and Coauthors, 2000; Tucker et al., 2001; Zhou et al., 2001, 2003). For example, linear trends of the data set in the Arabian Desert and Sahara did not show a significant change for either individual satellite or all satellites over the entire period from 1981–1999 (Slayback et al., 2003; Zhou et al., 2001). Similarly, we also examined this data set by checking interannual change in NDVI during 1982–2003 in the Taklimakan Desert, located in northwestern China, and confirmed the findings observed in the Arabian Desert and Sahara. These suggest that the effects related to changes in AVHRR sensor characteristics may be largely reduced. In addition, previous studies also indicated that NDVI is strongly correlated with aboveground biomass in Xinjiang (Ma et al., 2010; Piao et al., 2007; Shi, 2011), which suggests that the data set can be used to show interannual vegetation changes in our study area.

Monthly NDVI was obtained by the maximum value composite method, which minimizes cloud contamination, atmospheric effects, and solar zenith angle effects (Holben, 1986). These monthly NDVIs were then converted to geographic grid cells at 0.1° × 0.1° using the nearest-neighbor assignment resampling algorithm. In order to reduce the influence of sparsely vegetated grids on the NDVI trend, extremely dry deserts (grid cells with annual mean NDVI < 0.05) (Myneni et al., 1997; Piao et al., 2003) were excluded in this study. This generates the study area of 1,078,000 km^2, nearly 65% of the total area of Xinjiang. Further, to eliminate spurious NDVI trends because of winter snow, we only used the growing season NDVI (referred to as NDVI hereafter), generated from average monthly value from April to October, to analyze interannual vegetation changes.

Ordinary least-squares analyses were conducted to estimate linear time trends of NDVI and the three climate variables (temperature, precipitation and evapotranspiration) over the study period, and the significance level (p) of these variables was presented by F-test. Moreover, the absolute and percent NDVI and climate changes were measured as linear regression slope and the ratio of slope to the initial values. In addition, we calculated Pearson correlation coefficients between NDVI and climate variables and assumed that interannual variability in NDVI was related to temporal variability in climate variables if the correlation coefficients were statistically significant.

2.2. Climate, vegetation type, and bioregion data

Monthly temperature and precipitation were obtained from 54 climatic stations across Xinjiang (Fig. 1). Similar to Piao et al. (2003), we interpolated climate data to grid cells with a resolution of 0.1° × 0.1° using ordinary Kriging interpolation. The root mean squared error of the interpolation for monthly temperature and precipitation were 0.205 °C and 0.544 mm, respectively, based on cross-validation tests. Evapotranspiration (ET) is an effective good indicator for soil-moisture and available water condition, and we used the Thornthwaite method (Fang and Yoda, 1990; Thornthwaite, 1948) to calculate it for each pixel during the study period.

To obtain data on vegetation distribution, we digitized the Atlas of China's Vegetation with a scale of 1:1000000 (Editorial Committee for Vegetation Map of China, 2001), and then classified the vegetation in Xinjiang into five biome types: forest, shrub, grassland, desert, and cropland following criteria of the Atlas of China's Vegetation (Fig. 1). Because shrubs only occupy 0.7% of the total vegetation area, we excluded it from our analysis.

The spatial difference of vegetation cover is very large in Xinjiang because of complex geomorphology. To analyze vegetation changes according to biogeographic regionalization (Chai et al., 2008; Integrated Scientific Research Team of Xinjiang, 1978), we divided Xinjiang into six bioregions, Altai Mountain (Altai), Sawuer Mountain (Sawuer), Junggar Basin (Junggar), Tianshan Mountain (Tianshan), Tarim-Turpan Basin (Tarim), and Kunlun Mountain (Kunlun) (Fig. 1).

3. Results

3.1. Climate change

Over the past 22 years, obvious changes in temperature, precipitation and evapotranspiration (ET) were observed (Table 1). Annual mean temperature increased by 0.06 °C yr^{-1} ($p = 0.002$), while annual precipitation and ET increased with a rate of 1.35 mm yr^{-1} ($p = 0.056$) and 1.31 mm yr^{-1} ($p = 0.057$), respectively. Monthly mean temperature for all seasons except winter

Table 1
Linear trends in annual and seasonal temperature, precipitation, and evapotranspiration over the period 1982–2003 in Xinjiang, northwestern China.

Season	Temperature (°C)			Precipitation (mm)			Evapotranspiration (mm)		
	r^2	Slope	P-value	r^2	Slope	P-value	r^2	Slope	P-value
Spring	0.19	0.06	0.042	0.02	0.18	0.514	0.09	0.46	0.180
Summer	0.42	0.06	0.001	0.21	0.74	0.031	0.20	0.77	0.040
Autumn	0.24	0.06	0.021	0.02	0.13	0.542	0.01	0.09	0.681
Winter	0.15	0.07	0.074	0.28	0.28	0.011	–	–	–
Annual	0.40	0.06	0.002	0.17	1.35	0.056	0.17	1.31	0.057

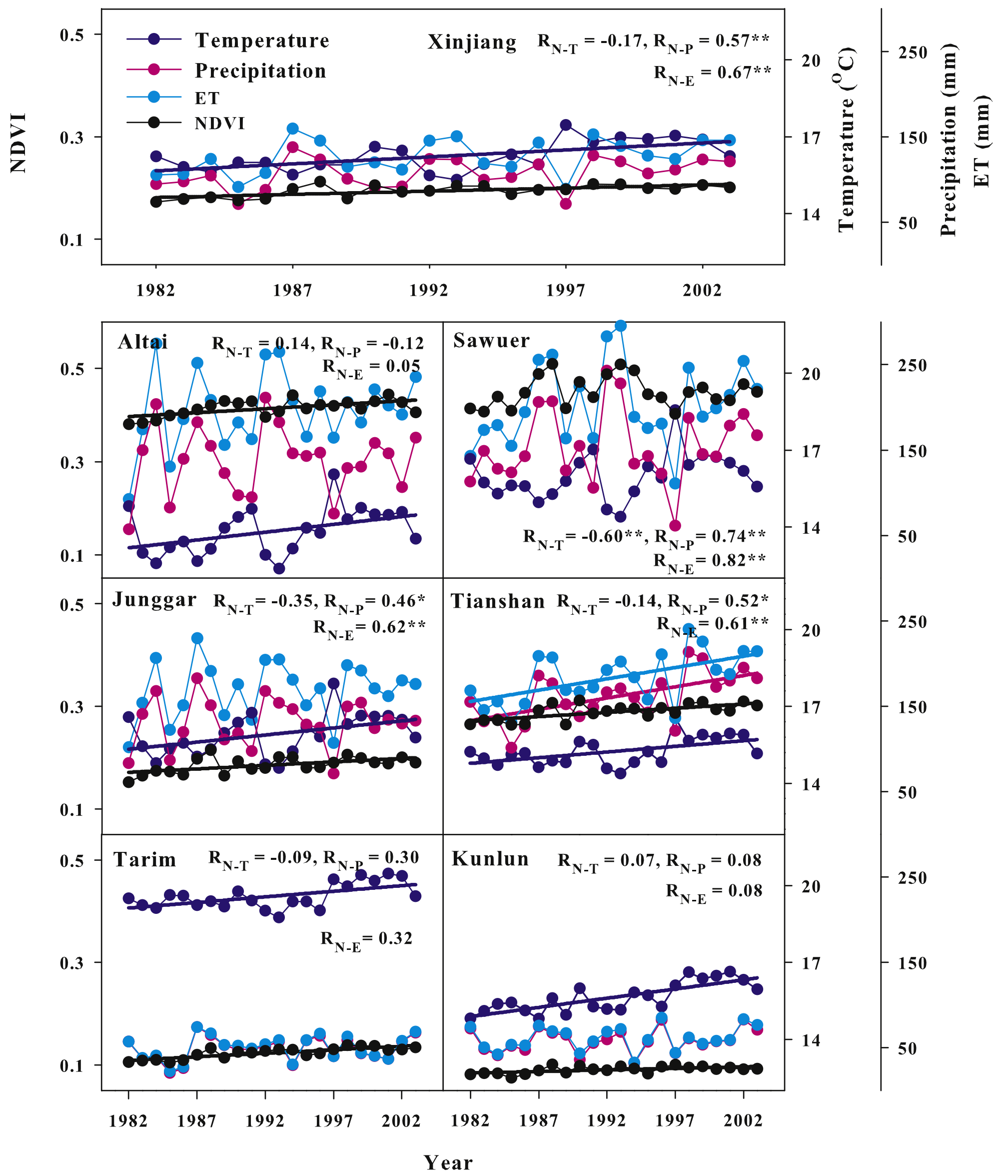

Fig. 2. Interannual variations of growing season NDVI (NDVI), growing season mean temperature (temperature), growing season precipitation (precipitation) and evapotranspiration (ET) in the whole area and different bioregions over the past 22 years. Trend lines denote linear time trends are significant at the 5% level. "RN-T", "RN-P" and "RN-E" are the correlation coefficients between NDVI and temperature, NDVI and precipitation, NDVI and ET. Double and single asterisks denote statistical significance at the 1% and 5% level, respectively.

significantly increased (spring by 14.2%; summer by 5.8%; and autumn by 19.2%). Precipitation increased by 0.74 mm yr^{-1} and 0.28 mm yr^{-1} in summer and winter ($p < 0.05$), with no clear trends in spring and autumn. As for seasonal ET, significant increase only appeared in summer with a rate of 0.77 mm yr^{-1}. The increases in these climate variables exactly support the view of warm-dry to warm-wet transition in this region (e.g. Shi et al., 2002, 2007).

3.2. NDVI changes in whole area

Interannual variations in NDVI over the past 22 years were analyzed to show the trend of vegetation growth in response to climate changes. Overall, NDVI increased significantly from 0.17 in 1982 to 0.20 in 2003, with an annual increase rate of 0.7% ($p = 0.001$). The increase was remarkable during 1982–1988, then tended to be slight, and finally a decline since 1998. This trend was consistent with the variation in growing season precipitation: precipitation increased before 1988, then stabilized between 1989 and 1998, and turned to a decline since 1999 (Fig. 2).

To evaluate the spatial heterogeneity of NDVI trends, we calculated the linear trend of NDVI against year (Fig. 3A) and its statistical significance level (5%, Fig. 3B) for each pixel. Large NDVI increases appeared in the southern parts of the Junggar basin, northwest Tarim basin, and central Tianshan Mountains. In contrast, an insignificant decrease occurred in middle parts of the Kunlun Mountains where climate is very dry. Overall, NDVI in 80% of the study area increased (30% with a significant increase), and only 1% of the study area indicated a significant decrease.

3.3. NDVI changes by bioregion and biome

The mean value and the interannual changes of NDVI varied with bioregions (Fig. 2). The large mean NDVI (0.41 unit) was observed in Altai and Sawuer where forests and grasslands cover

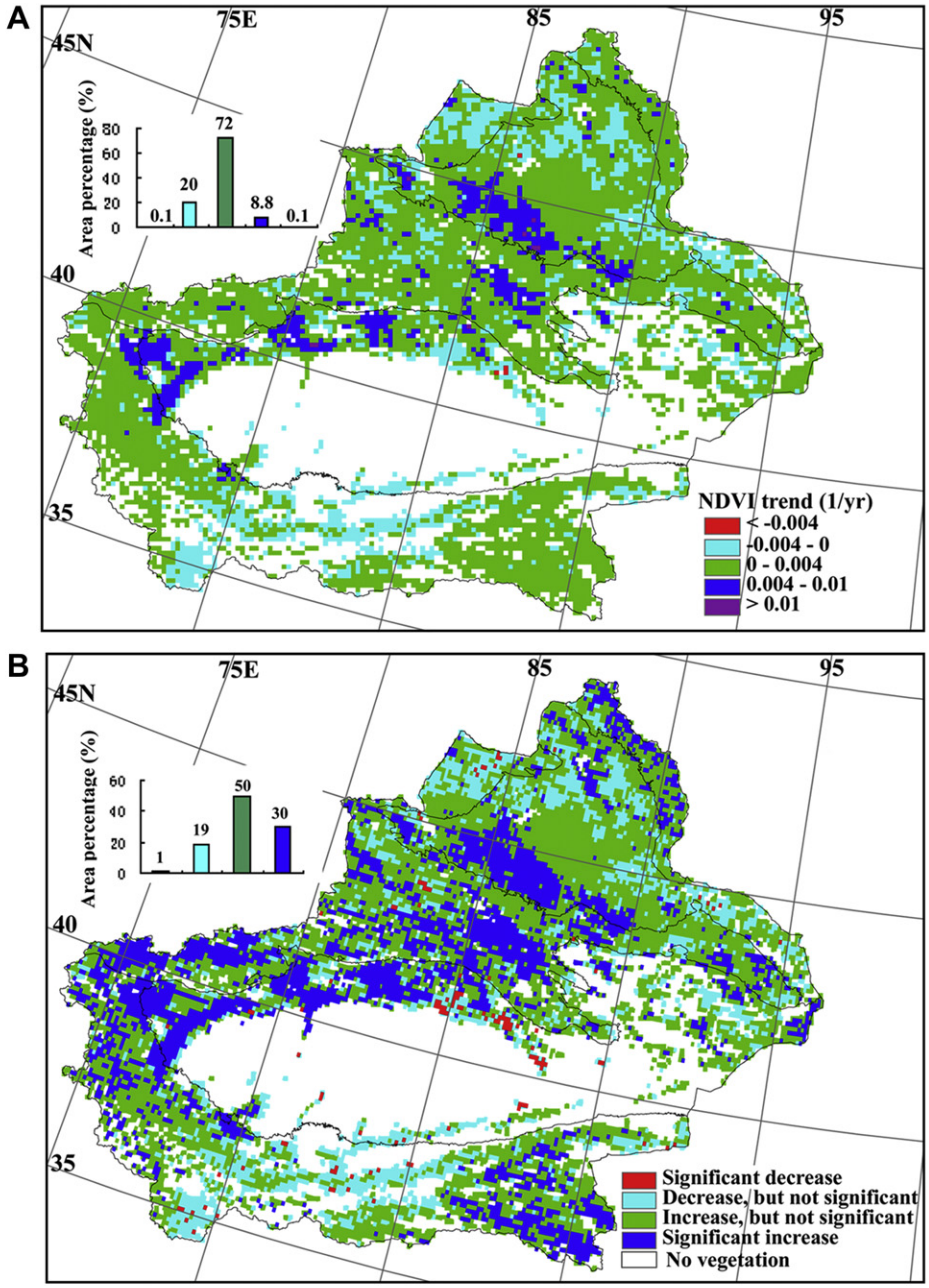

Fig. 3. Spatial patterns of growing season NDVI changing rates (A) and change rate at 5% significance (B) over the period 1982–2003. The inset graphs denote the area frequency distribution in each class of the changes.

most of these regions, while the lowest NDVI (0.10 unit) occurred in Kunlun where sparse vegetation dominates. On the other hand, NDVI showed an increasing trend for most bioregions except Sawuer, a core region of the study area with no significant climate change. The largest increase was in Altai and Tianshan, rising by 0.002yr^{-1} ($r^2 \geq 0.40$; $p < 0.01$), accompanied by a significant increase in both temperate and precipitation. The large increase in NDVI was also observed in Junggar and Tarim, both with an annual increase rate of 1% ($p < 0.01$). The human activities such as afforestation along riverside in these two regions may also have contributed to this increase.

At the biome scale, NDVI showed a remarkable increase over the 22 years for all biomes ($p < 0.05$) (Fig. 4). The large increases appeared in cultivated vegetation and forest, with an annual increase of 0.003 and 0.002, while others had a similar rate of nearly 0.001yr^{-1}.

3.4. Effects of climate change on NDVI trends

In order to explore natural controls of the NDVI trends, we correlated NDVI with the current growing season climatic changes at the three scales of whole region, biome and bioregion. At the scale of whole region, temperature was weakly correlated with NDVI ($r = -0.17$, $p = 0.45$), while it was significantly positively correlated with precipitation ($r = 0.57$, $p < 0.01$) and ET ($r = 0.67$, $p < 0.01$) (Fig. 2). A similar NDVI-climate relationship was found at the biome scale. At the bioregion scale, weak correlations between NDVI and temperature were observed in all bioregions except Sawuer where NDVI had a strongly negative relationship with temperature ($r = -0.60$; $p < 0.01$), while NDVI was positively correlated with precipitation ($p < 0.05$) and ET ($p < 0.01$) in Sawuer, Junggar, and Tianshan (Fig. 2).

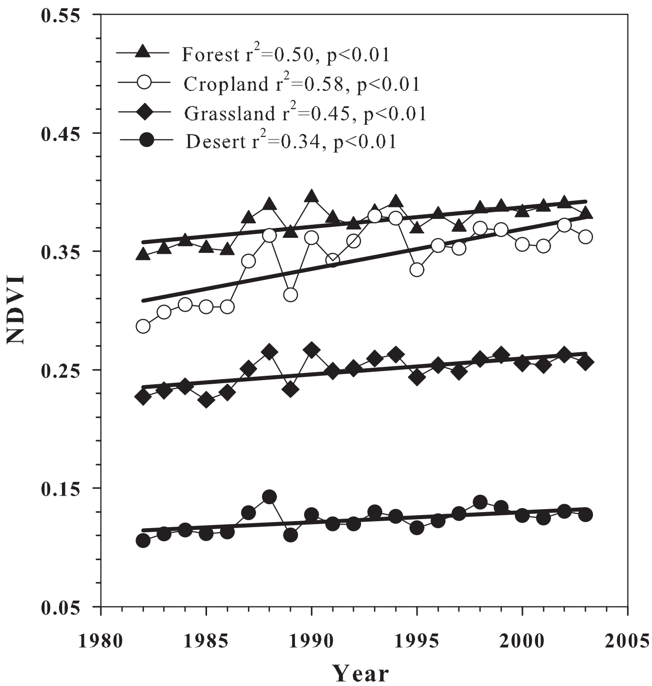

Fig. 4. Interannual variations of growing season NDVI for different biomes in Xinjiang from 1982 to 2003.

To detect the effects of seasonal climate variations on plant growth, we examined the relationships between detrended NDVI and seasonal (spring, summer, and autumn) temperature, precipitation and ET (Table 2). Considering a possible lag in the response of vegetation growth to seasonal climate conditions (Braswell et al., 1997; Zhou et al., 2003), we also investigated the correlation coefficients between NDVI and climatic variables in the preceding winter. For the total area, no significant correlation was exhibited between NDVI and mean temperature in all seasons except in the preceding winter ($r = 0.52$; $p < 0.05$). In contrast, NDVI was significantly correlated with seasonal precipitation except autumn, and the correlation between NDVI and seasonal ET was similar to that of precipitation (Table 2). The similar findings were observed at the biome scale. These results suggest that precipitation is a determinant controlling interannual variations in NDVI-indicated vegetation growth in the northwestern China.

4. Discussion and concluding remarks

The NDVI changes in the northwestern China during the past 22 years have provided a picture of the interannual variations in satellite-indicated vegetation growth in this region. First, NDVI showed a significant increase from 1982 to 2003 for the whole region (Fig. 2), consistent with previous findings (Deng et al., 2006; Fang et al., 2004). Second, NDVI tended to an increase for most bioregions except Sawuer (Fig. 2), where there was a large fluctuation in precipitation and vegetation growth was restricted by this fluctuation. Third, NDVI increased significantly for all biomes (Fig. 4). The mechanisms for this increase differed from those for different biomes. For example, the largest increase in NDVI occurred in cultivated vegetation probably because of intensive human managements (Ma et al., 2003). Warming-induced snowmelt plays a positive role in boosting plant growth for forests and meadows in subalpine areas (Li et al., 2003; Ren et al., 2007; Shi et al., 2007). The enhanced precipitation in winter and summer in recent years may induce increased growth for grasslands and desert vegetation (Hu et al., 2002).

Generally, there is a statistically significant positive correlation between NDVI and precipitation and ET, whereas the relationship between NDVI and temperature is very weak at both biome and bioregion scales (Fig. 2, Table 2). These findings are consistent with those from other semi-arid and arid ecosystems (Li et al., 2004; Méndez-Barroso et al., 2009; Nicholson et al., 1990; Wang, J. et al., 2003). Further investigation revealed that NDVI trend was positively correlated with precipitation received during the preceding winter, spring, and summer (Table 2). A strong degree of coupling between NDVI and seasonal ET during spring and summer was also shown in biomes and the total area. Additionally, we checked these relationships using areas of 2 × 2 pixels (256 km^2) centered at the meteorological stations (20 and 19 stations in grasses and desert vegetations, respectively), and the similar pattern was shown. These results are inconsistent with the global patterns because the previous studies suggested that NDVI responds positively to temperature increase in the Northern Hemisphere (Braswell et al., 1997; Zhou et al., 2001). Although warming-induced drought stress may exert negative effects on plant growth in arid and semi-arid ecosystems as revealed in our results and even in boreal forest (Barber et al., 2000), we noted that the growth of forests was correlated positively with the preceding winter temperature. The tree ring study also found the positive relationship between tree ring width and winter temperature (e.g. Wang et al., 2003), which supports our finding and suggests that increased winter temperature may enhance forest growth in the study area.

In summary, NDVI-indicated vegetation growth showed an overall increase over the past 22 years in the northwest China, and this increase was generally associated with change in precipitation and ET. This also supports a recent view of the warm-dry to warm-wet transition in this region (e.g. Shi et al., 2002, 2007). Previous analyses of satellite-measured vegetation growth suggested a greening trend of vegetation in the central United States (Wang et al., 2001, 2003) and the Sahel (Anyamba and Tucker, 2005; Herrmann et al., 2005) due to the effects of increasing precipitation at seasonal or annual scales. Moreover, the timing and magnitude of intra-seasonal precipitation pulses may differentially

Table 2
Correlation coefficients between detrended growing season NDVI and temperature (R_{NDVI-T}) and precipitation (R_{NDVI-P}) and evapotranspiration (R_{NDVI-E}) in different seasons for different biomes and the whole region (Double and single asterisks denote statistical significance at the 1% and 5% level).

Biome	R_{NDVI-T}				R_{NDVI-P}				R_{NDVI-E}		
	Win	Spr	Sum	Aut	Win	Spr	Sum	Aut	Spr	Sum	Aut
Forest	0.45*	0.02	−0.01	0.32	0.48*	0.48*	0.38	0.25	0.60**	0.42*	0.06
Grassland	0.54*	−0.25	−0.05	0.14	0.49*	0.52*	0.53*	0.15	0.67**	0.50*	0.02
Desert	0.31	−0.22	0.07	0.15	0.57**	0.64**	0.34	0.14	0.71**	0.46*	−0.06
Cropland	0.38	0.04	0.13	0.26	0.59**	0.47*	0.58**	0.06	0.62**	0.55**	−0.03
Total	0.52*	−0.29	−0.03	0.07	0.51*	0.59**	0.48*	0.14	0.70**	0.46*	−0.02

Win: the preceding Winter; Spr: Spring; Sum: Summer; Aut: Autumn.

affect ecosystem photosynthesis and respiratory (Huxman et al., 2004). Recent studies also revealed that seasonal phenological patterns were influenced by accumulated preceding precipitation in semi-arid and arid ecosystems (Jenerette et al., 2010).These findings, coupled with the observation in our study area, suggest that precipitation is likely to be a major determinant controlling NDVI change in water-limited ecosystems.

However, topographical features and changes in winter snow depth may create a spatial and temporal variation in soil-moisture conditions that governs the rate and magnitude of vegetation growth (Pennington and Collins, 2007; Peng et al., 2010). In addition to the effects of natural factors, enhanced anthropogenic activities in this area, such as land management, afforestation, and land abandonment, may also partly account for the observed increase in vegetation cover (Kong et al., 2009; Ren et al., 2007). For example, Jia (2004) showed that the decrease of abandoned cultivated land effectively prevented land desertification and improved the stability of oasis environments. Some other researchers suggested that highly uneven distribution and instability of runoff and river channel meandering in the Tarim River are entirely forced by human activities (Hao et al., 2008; Xu et al., 2010). Owing to the complexity of climate change and human intervention, the NDVI-climate relationships are not robust under many conditions, which suggests the large uncertainties in the correlation analysis presented in this study. Further work is required to quantify the relative contribution of the different driving factors, such as the human activities, to reduce these uncertainties.

Acknowledgments

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