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Article

Climate Contributions to Vegetation Variations in Central Asian Drylands: Pre- and Post-USSR Collapse

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Abstract: Central Asia comprises a large fraction of the world's drylands, known to be vulnerable to climate change. We analyzed the inter-annual trends and the impact of climate variability in the vegetation greenness for Central Asia from 1982 to 2011 using GIMMS3g normalized difference vegetation index (NDVI) data. In our study, most areas showed an increasing trend during 1982–1991, but experienced a significantly decreasing trend for 1992–2011. Vegetation changes were closely coupled to climate variables (precipitation and temperature) during 1982–1991 and 1992–2011, but the response trajectories differed between these two periods. The warming trend in Central Asia initially enhanced the vegetation greenness before 1991, but the continued warming trend subsequently became a suppressant of further gains in greenness afterwards. Precipitation expanded its influence on larger vegetated areas in 1992–2011 when compared to 1982–1991. Moreover, the time-lag response of plants to rainfall tended to increase after 1992 compared to the pre-1992 period, indicating that plants might have experienced functional transformations to adapt the climate change during the study period. The impact of climate on vegetation was significantly different for the different sub-regions before and after 1992, coinciding with the collapse of the Union of Soviet Socialist Republics (USSR). It was suggested that these spatio-temporal patterns in greenness change and their relationship with climate change for some regions could be explained by the changes in the socio-economic structure resulted from the USSR collapse in late 1991. Our results clearly illustrate the combined influence of climatic/anthropogenic contributions on vegetation growth in Central Asian drylands. Due to the USSR collapse, this region represents a unique case study of the vegetation response to climate changes under different climatic and socio-economic conditions.

Keywords: climate change; vegetation greenness; GIMMS3g NDVI; USSR collapse

1. Introduction

Central Asia comprises one of the most important drylands in the world, accounting for nearly 1/10 of the total dryland area in the planet [1]. This region feeds over 64 million people, with its population expected to reach 87 million in 2050 (FAO, [2]). Central Asia is a moisture-limited ecosystem dominated by steppes, semi-deserts, and deserts [3], and represents an important carbon reservoir, playing a significant role in the global carbon cycle [4]. However, large fluctuations in vegetation greenness have been recently observed in this region. Comparing with the greenness variation in 1982–2006 in Eurasia, Piao *et al.* [5] noted a turning point in the normalized difference vegetation index (NDVI) trajectory for Central Asia in 1992–1996, when the greenness started to decrease. Significant negative trends in vegetation greenness continued for large parts of Central Asia since the beginning of the 20th century [6,7].

Many studies have shown that drylands in Central Asia are especially sensitive and susceptible to climate change and environmental degradation [8–10]. Continuous increases in temperature contributed to increased evapotranspiration in this region. Thus, shortage of water resources and aridity are expected to be intensified [4,11–14]. Under such circumstances, Eisfelder *et al.* [15] pointed out that temperature is an important factor for plant net primary productivity (NPP) during spring in Kazakhstan. Although precipitation is highly variable [4,11], several studies have found that the plants in Central Asia are sensitive to precipitation anomalies and exhibit lagged responses for most areas [15–18]. However, studies on the combined impact of temperature and precipitation on the vegetation greenness in Central Asia are limited so far.

In addition to climate change, the collapse of Union of Soviet Socialist Republics (USSR) in 1991 was another pivotal factor affecting plant growth [19]. Given the political, economic, and social instability post-USSR collapse, terrestrial ecosystems became particularly vulnerable to human disturbance, such as land-use changes [11,20,21]. Vast areas of ploughed land in Kazakhstan, used as extensive farmland during the USSR period, were abandoned because of the reduction in population following the USSR collapse [19,22,23]. Accordingly, significant differences in the vegetation greening trend [5,24] and phenology were found in Central Asia for the pre- and post-USSR collapse [25]. Thus, a deeper understanding of the challenges faced by Central Asian countries following the USSR collapse is crucial for designing a comprehensive adaptation strategy to contemporary climate change in the broader context of sustainable development. However, an assessment of the different mechanisms driving the vegetation response to climate change under different socio-economic circumstances has received little attention in the scientific literature.

This study addresses the need to assess the terrestrial vegetation response to climate variations in Central Asia pre- and post-USSR collapse. More specifically, we aimed to (1) investigate the long-term changes in vegetation, especially for grasslands and croplands, and (2) determine the contribution of climatic factors to vegetation growth during 1982–2011, which encompasses pre- and post-USSR collapse periods.

2. Data and Methods

2.1. Study Area

Central Asia constitutes the core region of the Asian continent, spanning from the Caspian Sea in the west to China in the east and from Afghanistan in the south to Siberia in the north (Figure 1). Our study area included five countries: Kazakhstan, Uzbekistan, Turkmenistan, Tajikistan, and Kyrgyzstan. Its mean summer temperatures range from 20 °C in the north to above 30 °C in the south [26], while during winter they are below zero, with extremes below −20 °C in the northern and mountain areas. The mean annual precipitation in the lowlands ranges between ~400 mm in north of Kazakhstan and less than 100 mm in some areas of Uzbekistan and Turkmenistan [11,26].

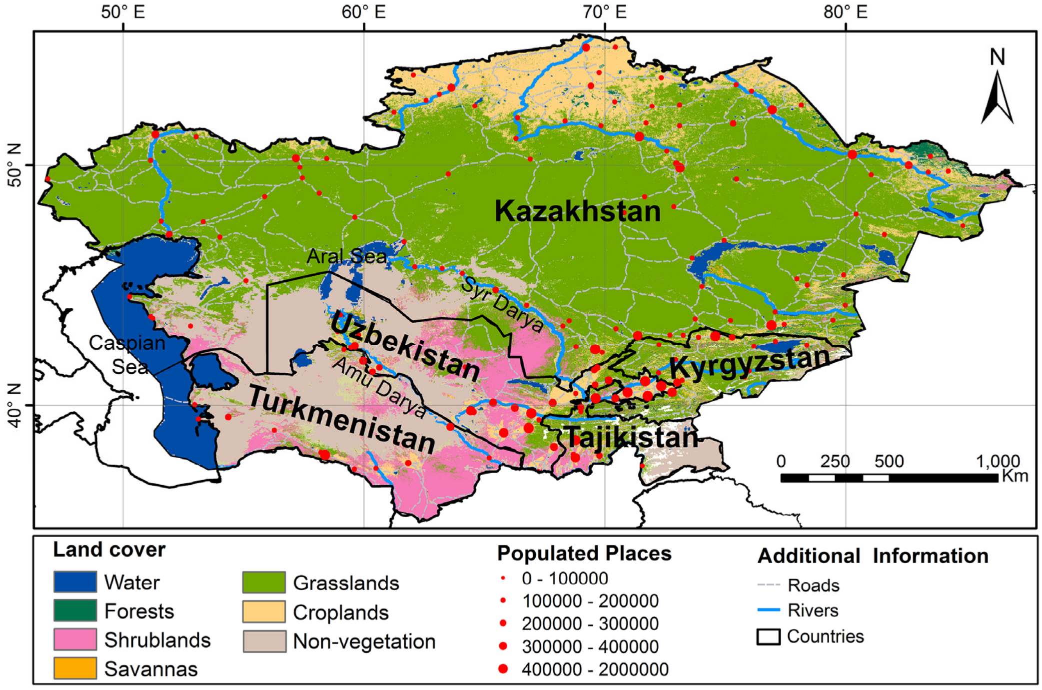

Figure 1. Map of study area. The land cover data was adapted from the 500 m Moderate Resolution Imaging Spectroradiometer (MODIS) land cover product (MCD12Q1). Data for population, roads, rivers, lake centerlines, and country boundaries were downloaded from the Natural Earth database [27].

Central Asia has approximately 6000 lakes, most of which are inland lakes [28]. Water originating from snow melting in the mountains is provided to the lowland lakes by rivers, with upstream storage reservoirs used for agricultural irrigation. However, more than half of inland lakes have experienced significant decreases since 1975 [29], exacerbating serious environmental issues such as soil salinization, pollution of water sources [30], frequent drought, and land degradation [11].

According to the Moderate Resolution Imaging Spectroradiometer (MODIS) land cover map (MCD12Q1), barren lands occupy most Uzbekistan and Turkmenistan. Regarding the vegetation, grasslands account for 60.6% of the total territory in Central Asia, followed by croplands (12.0%), shrublands (9.5%), and forests (1.0%) (Figure 1). Grasslands occupy considerable areas of Kazakhstan, Tajikistan, and Kyrgyzstan. The dominant crop types is rain-fed that include wheat, oats, and barley in northern Kazakhstan, while along Amu Darya and Syr Darya (mainly in Turkmenistan, Uzbekistan, and southern Kazakhstan) vast areas are used for irrigated crops (e.g., cotton and rice).

2.2. Data

2.2.1. GIMMS3g NDVI Data

The GIMMS3g NDVI dataset, available from July 1981–December 2011, is the latest NDVI product released by the NASA Global Inventory Modeling and Mapping Studies (GIMMS) group. The dataset was generated by an Advanced Very High Resolution Radiometer (AVHRR) onboard a series of National Oceanic and Atmospheric Administration (NOAA) satellites (NOAA 7, 9, 11, 14, 16, 17, and 18). To avoid the effects caused by the use of different sensors changes between the NOAA satellites and orbital decay on the quality of the AVHRR data, several procedures were performed to minimize the deviation. Specifically, a satellite orbital drift correction was performed using the empirical mode decomposition (EMD)/reconstruction method, which minimizes the effects of orbital drift by removing the common trends between the time series for the solar zenith angle (SZA) and NDVI [31,32]. Additionally, corrections were applied for volcanic stratospheric aerosol effects from the El Chichon (1982–1984) and Mt. Pinatubo (1991–1993) volcanic eruptions [31]. Calibration was performed using SeaWiFS data, as opposed to earlier GIMMS NDVI datasets, which were based on inter-calibration with the SPOT sensor [33].

The GIMMS3g NDVI dataset (1982–2011) has a spatial resolution of 1/12° and a temporal resolution of 15 days, and is currently considered the best dataset available for long-term NDVI trend analysis [33]. The GIMMS3g NDVI dataset has already been shown to accurately represent the real responses of vegetation to climate variability [34].

In this study, we aggregated the NDVI data to monthly observations for the entire study area in 1982–2011 using the maximum value composition, further reducing cloud and other noise effects. We calculated the annually and seasonally averaged NDVI for each year. Since in Central Asia the vegetation growing season starts around April/May and lasts until October, when temperatures drop and snow cover blocks the absorption of incoming photosynthetically active radiation (APAR), effectively stopping vegetation growth [7,17,35]. Therefore, seasonal NDVI was calculated as the mean NDVI for spring (April–May), summer (June–August), and autumn (September–October).

2.2.2. Climate Data

Climate data were derived from the Modern Era Retrospective-Analysis for Research and Applications (MERRA) project at the Global Modeling and Assimilation Office (GMAO; [36]). The MERRA reanalysis dataset uses observations from NASA's Earth Observing System satellites and reduces the uncertainty in precipitation data for the water cycle, with significant improvements since the previous generation of datasets [37].

Meteorological data from MERRA have a spatial resolution of 0.5° × 0.667°, covering from 1979 to present. In this study, we used monthly temperature and precipitation data for 1982–2011. The climate data were resampled to ensure a 1/12° spatial resolution consistent with the GIMMS3g NDVI data and were used to explore the impact of climate on the vegetation greenness. Generally, the climate variables have relatively smooth transition in space in Central Asia, especially for temperature. Interpolation is a more suitable method for climate data and has been commonly used in regional climate studies. Similar to the NDVI, we calculated the annual and seasonal total precipitation and mean temperature for each year for 1982–2011 using the monthly data.

2.3. Methods

2.3.1. Trend Analysis of NDVI and Climatic Factors

We identified the regions with significant annual and seasonal NDVI trends in 1982–2011 using linear regression:

$$y = a + bx + \varepsilon \tag{1}$$

where y was a dependent variable representing the annual or seasonal NDVI (or climate variable) and x was the independent variable representing the year. The parameter b was the slope of the regression line, a was the intercept, and ε represented the error term. In this linear model, we adopted the least absolute deviation (LAD) method, which requires the deviation minimum, in comparison with the least-squares method. For large dispersion data, the values fitted with the LAD method are closer to the real values [38]. The LAD method is also more powerful than least-squares for asymmetric error distributions and heavy-tailed, symmetric error distributions, and more resistant to the influence of outliers in the dependent variable [38–41].

The LAD linear regression model was applied to all pixels in the time-series images and maps of the annual and seasonal trends of NDVI and climate variables were created to show the positive (increasing) or negative (decreasing) trends in the data. Then, we conducted an analysis of the regional trends by focusing on the spatially averaged time series for NDVI, temperature, and precipitation.

2.3.2. Multiple- and Partial-Correlation Analysis for the Climatic Impact on Vegetation

To quantify the effect of rainfall and temperature on the greenness trends, we used multiple correlation regression to simulate their relationships (Equation (2)). In this equation, x_1 and x_2 represented the precipitation and temperature, respectively, and y represented the NDVI. $\hat{y_i}$ was the simulated NDVI by the regression of x_1 and x_2. The multiple-correlation coefficient (R) was calculated by Equation (3). The significance of the correlation coefficient was estimated by an F-test at a significance level of 95%, with a larger coefficient representing a closer relationship between NDVI and climate.

$$\hat{y}_i = b_0 + b_1 x_1 + b_2 x_2 \tag{2}$$

$$R = \frac{\sum(y_i - \bar{y}) - \sum(\hat{y}_i - \bar{y})}{\sqrt{\sum(y_i - \bar{y})^2 \sum(\hat{y}_i - \bar{y})^2}} \tag{3}$$

However, multiple correlation cannot identify negative or positive relationships as its ranges 0–1. Thus, we adopted a partial correlation coefficient to demonstrate the contribution of each climatic factor to the vegetation greenness. Partial correlation measured the degree of association between two variables without the influence of the other factor as follows:

$$r_{x_1 y.x_2} = \frac{r_{x_1 y} - r_{x_1 x_2} r_{x_2 y}}{\sqrt{1 - {r_{x_1 x_2}}^2}\sqrt{1 - {r_{x_1 y}}^2}} \tag{4}$$

where $r_{x_1 y}$, $r_{x_2 y}$, and $r_{x_1 x_2}$ are the correlation coefficients between NDVI and one climatic factor (e.g., precipitation), NDVI and the other climatic factor (e.g., temperature), and the two climatic factors, respectively, and $r_{x_1 y.x_2}$ is the partial correlation coefficient between one climatic factor and NDVI, excluding the other climatic factor. A *t*-test was adopted to test the partial correlation coefficients, whose significance was estimated at a level of 95%.

2.3.3. Time-Lag Correlation Analysis between NDVI and Precipitation

The relationship between NDVI and precipitation is characterized by a time-lag response of NDVI in relation to rainfall, since the vegetation is affected by both current and previous events. Moreover, this relationship can differ significantly depending on the plant growth stage [42,43]. Thus, the relationship between NDVI and precipitation was depicted by:

$$NDVI_t = f(P_t, P_{t-1}, P_{t-2}, \cdots, P_{t-k}, d) + \varepsilon_t \tag{5}$$

where $NDVI_t$ is the NDVI value at time *t*, P_{t-k} is the precipitation volume at time $t - k$, *k* is the lag length, *d* is the date during the growing season, and ε_t is the random error. In our study, we simplified this relationship for each month during the growing season according to Gessner *et al.* [17]:

1. The relationship between NDVI and precipitation was analyzed through partial correlation according to Equation (2). The time-lagged correlations were performed for four different month lags (lag 0, lag 1, lag 2, and lag 3) for each pixel. For each lag effect, we considered the cumulative effect of 1–5 months [17], resulting in 20 lag-correlations for all conditions (Figure 2).
2. To assess the most accurate lag-response of the vegetation to precipitation changes, we adopted the maximum correlation coefficient of the 20 correlation analyses for each pixel.
3. Through the maximum correlation coefficient, we determined the lag time from the 20 lag-correlation results. The lag effects were illustrated by the maximum correlation coefficient and corresponding lag time.

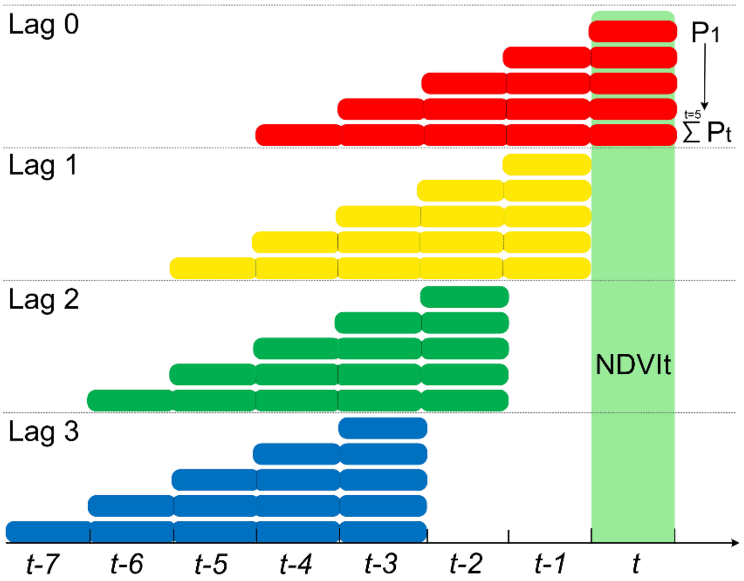

Figure 2. Schematic presentation of the lag effect of precipitation on NDVI. The horizontal bars represent the precipitation time series. The vertical bar represents the NDVI at time *t*. The impact of lag 0, 1, 2, and 3 on the NDVI is represented by the colors red, yellow, green, and blue, respectively. For example, lag 0 represented monthly NDVI values at time *t* were correlated with the precipitation from time *t* (concurrent month) to time $t - 1$ (previous one month), or $t - 2$ (previous two month), or $t - 3$ (previous three month), or $t - 4$ (previous four month).

3. Results

3.1. Annual Trends in the Climatic Factors and NDVI

The annual total precipitation and annual mean temperature from the MERRA dataset were calculated for 1982–2011 (Figures 3(a1,b1)). The annual total precipitation varied from 11 mm in the lowlands of Uzbekistan to over 800 mm in the high mountain grasslands of the southern regions. Temperature exhibited an opposite spatial pattern to precipitation. Low temperatures were found for the high latitude and mountainous areas where the annual mean temperature reached below zero. High temperatures were found for the southwestern areas of Central Asia where the annual total precipitation was generally below 200 mm.

Precipitation showed a high spatial heterogeneity trend during 1982–2011 (Figure 3(a2)). Positive trends were concentrated in the southwest and east regions, while negative trends widely occurred across the majority of Central Asia, such as in the grasslands of Kazakhstan and Tajikistan. The regional averaged total precipitation decreased significantly (p-value < 0.05) in 1982–2011 (Figure 3(a3)). Concurrently, a significant warming trend was detected with an increasing rate of 0.052 °C/yr (p-value < 0.05) (Figure 3(b3)) and covering over 90% of the vegetated areas in Central Asia (Figure 3(b2)). Overall, the climate in Central Asia was characterized by a warming and drying trend during 1982–2011.

The NDVI was relatively high for the northern high latitudes of Kazakhstan and southern Central Asia, where rainfall was sufficient and temperature was relatively low compared to middle Central Asia (Figure 4a). Relatively low NDVI values appeared mainly in central and southwestern Central Asia, mostly in shrubland areas, with little annual rainfall (0–150 mm) and high annual temperatures (10–20 °C) (Figure 3(a1,b1)).

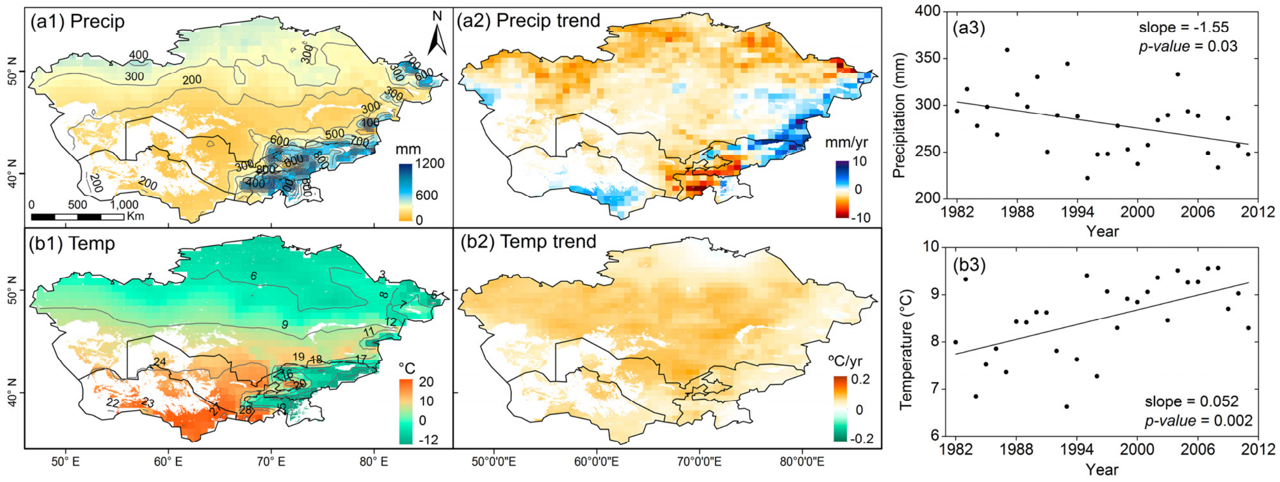

Figure 3. (**a1**,**b1**) Annual total precipitation (Precip) and annual mean temperature (Temp) for 1982–2011. (**a2**,**b2**) Annual trends. (**a3**,**b3**) Time series of the annual total precipitation and annual mean temperature.

Statistically, NDVI exhibited large inter-annual fluctuations during 1982 and 2011 (Figure 4b). Before 1991, the vegetation showed a greenness increase of up to 0.017/yr (p-value = 0.14). After 1991, there was an obvious decrease in greenness over Central Asia at a rate of −0.009/yr (p-value = 0.05). To evaluate the spatial heterogeneity of the NDVI trends, a linear NDVI trend was calculated for each pixel during 1982–1991 and 1992–2011. The vegetation greenness experienced significant upward trends for 9.0% of the total vegetated area in Central Asia during 1982 and 1991 (Figure 4(c)). However, a downward trend in greenness was observed in 1992–2011 (Figure 4c,d). During 1992–2011, the vegetated areas with significantly browning trends (p-value < 0.05) dramatically increased to 22.9% of all vegetated area. The areas with non-significantly decreasing NDVI trends also expanded to cover 48.2% of all vegetated area. Significantly decreasing trends were mainly found for most north Kazakhstan and the Aral Sea Basin.

The various vegetation types changed differently in Central Asia. During 1982–1991, significantly positive greenness trends were observed for the following vegetation type areas: grasslands (7.3%), croplands (16.7%), shrublands (5.1%), and forests (34.8%) (Figure 5(a)). However, significant decreases in NDVI were found for these four areas in 1992–2011: grasslands (21.5%), croplands (36.5%), shrublands (24.3%), and forests (18.8%). Grassland is the dominating vegetation type in Central Asia. In 1982–1991, grassland areas showed barely significantly (p-value < 0.05) decreasing trends (Figure 4 and 5). But after 1992, the decreasing trends expanded to large areas accounted for 21.3% of grassland areas in Central Asia. This phenomenon was mainly apparent for the lowland areas of Kazakhstan, whereas the high mountain grassland areas in the east, such as Kyrgyzstan and east Kazakhstan, showed very limited decreasing trends.

In addition, croplands suffered the largest decrease in 1992–2011 and a detailed statistical analysis of cropland data was performed for the five Central Asian countries (Figure 5b). Before 1991, significantly positive trends in NDVI were observed for over 10% of the croplands in all countries. However, decreasing greenness trends were observed in croplands for the five countries after the USSR collapse. The largest percentage of negative trends for Central Asia was observed in Kazakhstan, where 47.7% of croplands showed a significant greenness decrease. Most browning croplands corresponded to rain-fed agricultural areas in northern Kazakhstan (Figure 1). A decreasing greenness was also apparent for croplands in Tajikistan (4.3%), Uzbekistan (5.6%), Kyrgyzstan (3.3%), and Turkmenistan (3.4%). As the climatic variation was similar for these two periods, these differences in greenness changes might have additionally been caused by other factors, such as land-use and water supplement changes.

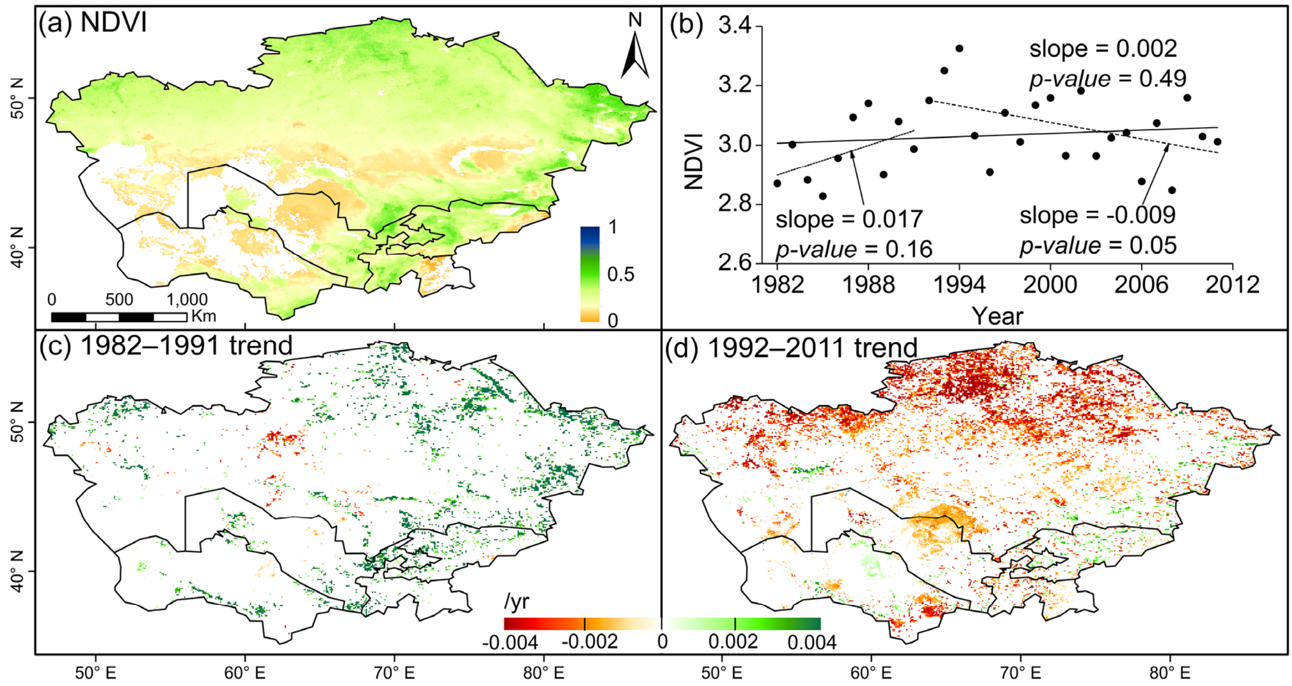

Figure 4. (**a**) Map of the annual NDVI and (**b**) spatially averaged NDVI trend for 1982–2011. (**c**,**d**) represent the maps of the annual NDVI linear trends for 1982–1991 and 1992–2011, respectively. The areas with significant trend correspond to a *p*-value < 0.05.

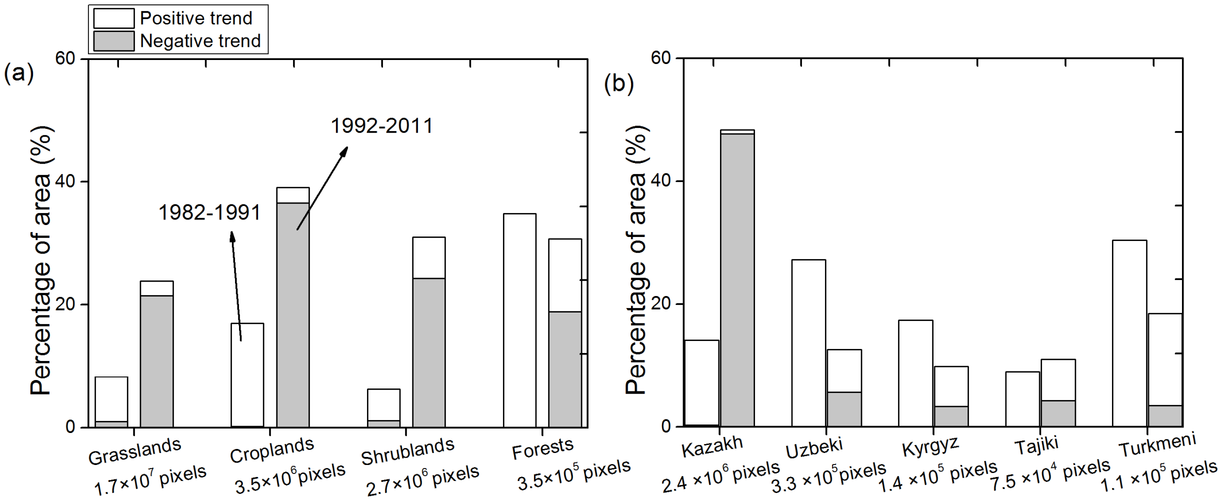

Figure 5. Percentage of the area with significantly positive (white) and negative trends (gray) (*p*-value < 0.05) during 1982–1991 (left columns) and 1992–2011 (right columns) for the (**a**) dominant land cover types (with the number of pixels below) and (**b**) croplands in Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, and Uzbekistan.

3.2. Seasonal Trends in the Climatic Factors and NDVI

To verify the seasonal greenness contributions to the annual variation, we investigated the seasonal variation in the climatic factors and NDVI during 1982–1991 and 1992–2011. In spring, the mean precipitation was relatively lower (3.8 mm) in 1992–2011 than in 1982–1991 (Figure 6). However, the climate became warmer (1.0 °C) in 1992–2011, at a significant increasing rate of 0.2 °C/yr (p-value < 0.05), with over 40% of the vegetated areas characterized by a significantly warming trend (p-value < 0.05) (Table 1). Accordingly, the area with a significant greening trend increased from 4.5% in 1982–1991 to 17.5% in 1992–2011.

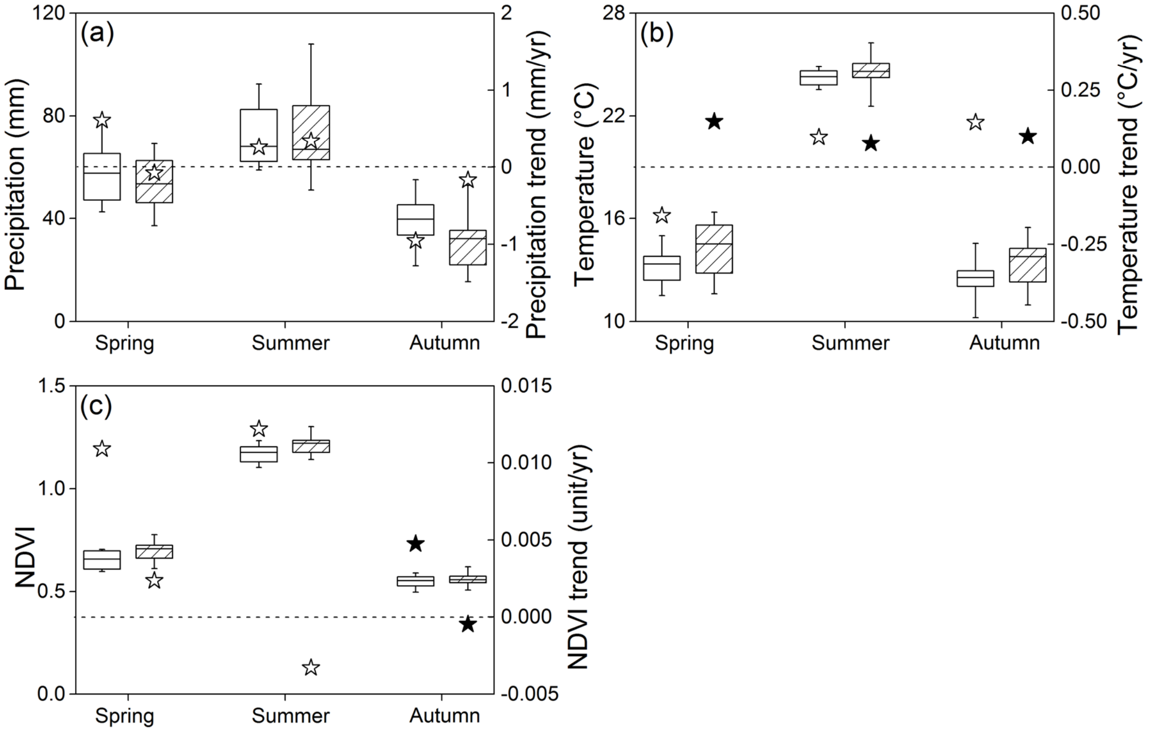

Figure 6. Inter-annual variations and trends for the seasonal (**a**) precipitation, (**b**) temperature, and (**c**) NDVI in 1982–1991 and 1992–2011 in Central Asia. The boxes represent the values for the second and third quartiles, the horizontal line gives the median, and the whiskers show the lowest/highest values. The hollow stars indicate the temporal trends in precipitation, temperature, and NDVI for the different seasons, while the solid stars show the significant trends (p-value < 0.05).

Precipitation did not show large spatio-temporal changes during summer (Figure 6; Table 1). Similar to spring, the summer temperature significantly increased at a rate of 0.08 °C/yr in 1992–2011 (p-value < 0.05). However, the vegetation showed dramatically different trends for these two periods. During 1982–1991, the NDVI showed a non-significant increasing trend, with 7.9% of the vegetated areas showing a significantly greening trend. However, in 1992–2011, the NDVI trend significantly decreased at a rate of −0.3 unit/yr with 13.5% of the area characterized by a significant browning trend.

In autumn, the precipitation was much lower (9.6 mm) in 1992–2011 than in 1982–1991. The temperature was higher (0.8 °C) in 1992–2011, with over 75% of the vegetated areas showing significantly warming trends. Similar to summer, the NDVI trends in autumn differed for the two periods. In 1982–1991, NDVI had a significantly increasing rate of 0.5 unit/yr, with 13.5% of the vegetated areas showing significantly greening trends. Nevertheless, in 1992–2011, the vegetation NDVI decreased at a rate of −0.05 unit/yr, with 27.1% of the vegetated areas characterized by significantly browning trends.

The warming condition and relatively higher precipitation promoted seasonal greenness in 1982–1991. Accordingly, in 1982–1991, the annual greening trend resulted from all the three seasonal greening trends. However, the slightly decreasing precipitation in spring and summer contributed to the dryer conditions in 1992–2011. Comparing the temperature variations for the three seasons, the seasonal warming trends were more severe in 1992–2011 than in 1982–1991, especially in autumn. Therefore, in 1992–2011, even though 17.5% of the vegetated areas showed a significantly greening trend in spring, the decreasing greenness in summer and autumn led to an annual decrease in NDVI.

Table 1. Area percentage of significantly (p-value < 0.05) positive (+) and negative (−) trends for precipitation (Precip), temperature (Temp), and NDVI for all Central Asian vegetated areas in 1982–1991 and 1992–2011.

	Trend	**Spring**		**Summer**		**Autumn**	
		1982–1991	**1992–2011**	**1982–1991**	**1992–2011**	**1982–1991**	**1992–2011**
Precip	+	0.0%	0.5%	0.1%	0.3%	0.0%	0.5%
	−	0.1%	0.6%	0.0%	0.6%	0.5%	1.5%
Temp	+	1.1%	**43.9%**	1.8%	**41.9%**	**16.2%**	**78.9%**
	−	3.6%	0.0%	0.0%	0.8%	0.0%	0.0%
NDVI	+	4.5%	**17.5%**	7.9%	4.5%	**13.5%**	3.6%
	−	0.5%	7.2%	0.3%	**13.5%**	0.4%	**27.1%**

3.3. Climate Impact on the Vegetation Greenness.

Based on the multiple correlation analysis, in 1982–1991, only 3.3% of the vegetated area was significantly affected by climate (p-value < 0.05) (Figure 7(a1)). However, the vegetated region significantly affected by climate expanded to 5.6% in 1992–2011 (Figure 7(b1)), mainly in south Kazakhstan and north Uzbekistan, within the Amu Darya and Syr Darya basins. But for most areas in northern Kazakhstan, the degree of climatic impact on greenness was evidently lower in 1992–2011 than that in 1982–1991.

To distinguish the individual contributions of precipitation and temperature from their combined effect, Figure 7(a2,b2) show the partial correlation between NDVI and precipitation for the two periods, excluding the effect of temperature. In 1982–1991, the precipitation showed positive effects on the vegetation greenness in 5.1% of the vegetated areas in Central Asia, but it expanded to 11.5% of the vegetated areas in 1992–2011. These expanded areas mainly located in Amu Darya and Syr Darya basins, where croplands are irrigated. Comparing the spatial patterns of the affected areas by the combined climate effect during these two periods (Figure 7(a1,b1)), the expanded areas coincided with the areas affected by precipitation changes (Figure 7(a2,b2)), which implied that precipitation was the main factor of climatic impact on greenness of these regions.

Figure 7(a3,b3) show the partial correlation between NDVI and temperature for the two periods, excluding the effect of precipitation. Temperature had dramatically different impacts for the two periods. For the first period, the temperature showed strong positive effects on vegetation growth for most areas, while its consistent increase resulted in negative effects in 1992–2011 for most areas and especially for Kazakhstan grasslands. The vegetation greenness might then have been suppressed by the significant warming trend in 1992–2011.

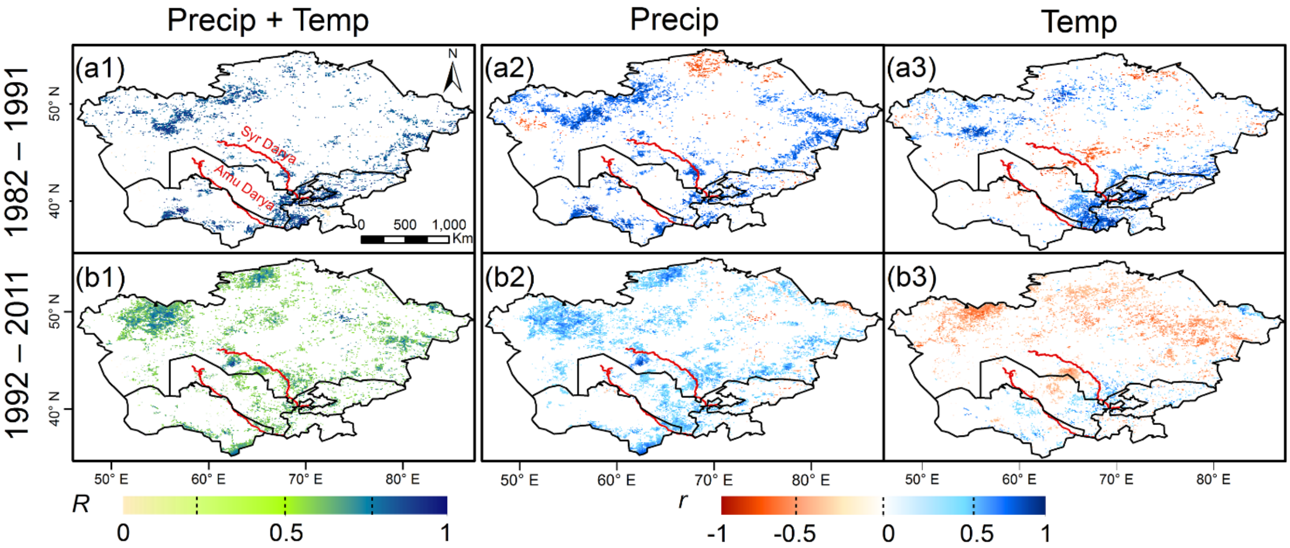

Figure 7. NDVI response to (**a1**,**b1**) combined precipitation and temperature (*R*), (**a2**,**b2**) precipitation (*r*), and (**a3**,**b3**) temperature (*r*) during 1982–1991 and 1992–2011. The areas with significant correlations correspond to a *p*-value < 0.05.

Overall, climate had a generally weak correlation with greenness in northern Kazakhstan areas in 1992–2011 compared to 1982–1991. But the correlation between precipitation and greenness became stronger in some areas such as the Amu Darya and Syr Darya basins. In addition, temperature showed evidently opposite impacts on greenness during the two periods and the warming condition turned from a promoter in 1982–1991 to a suppressant in 1992–2011 for vegetation greenness.

3.4. Lagged-Response of NDVI to Precipitation

Considering vegetation have lagged responses to rainfalls, we further studied the relationship between vegetation and precipitation in 1982–1991 and 1992–2011. Figure 8 presents the lagged maximum correlations and months of NDVI response to precipitation. Generally, in Central Asia, the correlation between NDVI and precipitation was positive in May–September. However, the precipitation and NDVI were negatively correlated in April and October for most vegetated areas, and especially for grasslands in Kazakhstan. Additionally, the significantly correlated areas increased from April–June and declined until October, with the largest areas in June (43.3% in 1982–1991 and 52.7% in 1992–2011 for all vegetated areas) (Figure 8(c1)–(c4)).

Many areas were characterized by a strong sensitivity of NDVI to rainfall ($r > 0.7$) in 1982–1991 (Figure 8). In contrast to the time-lagged response of greenness to precipitation in 1982–1991, strong correlations were only observed for northwest Central Asia in 1992–2011 (Figure 8), indicating a weaker impact of precipitation on NDVI for the second period. However, there was a larger percentage of vegetated areas affected by precipitation after 1992 than before 1992. This expansion was mostly located in central and south Central Asia, where the NDVI was comparatively lower.

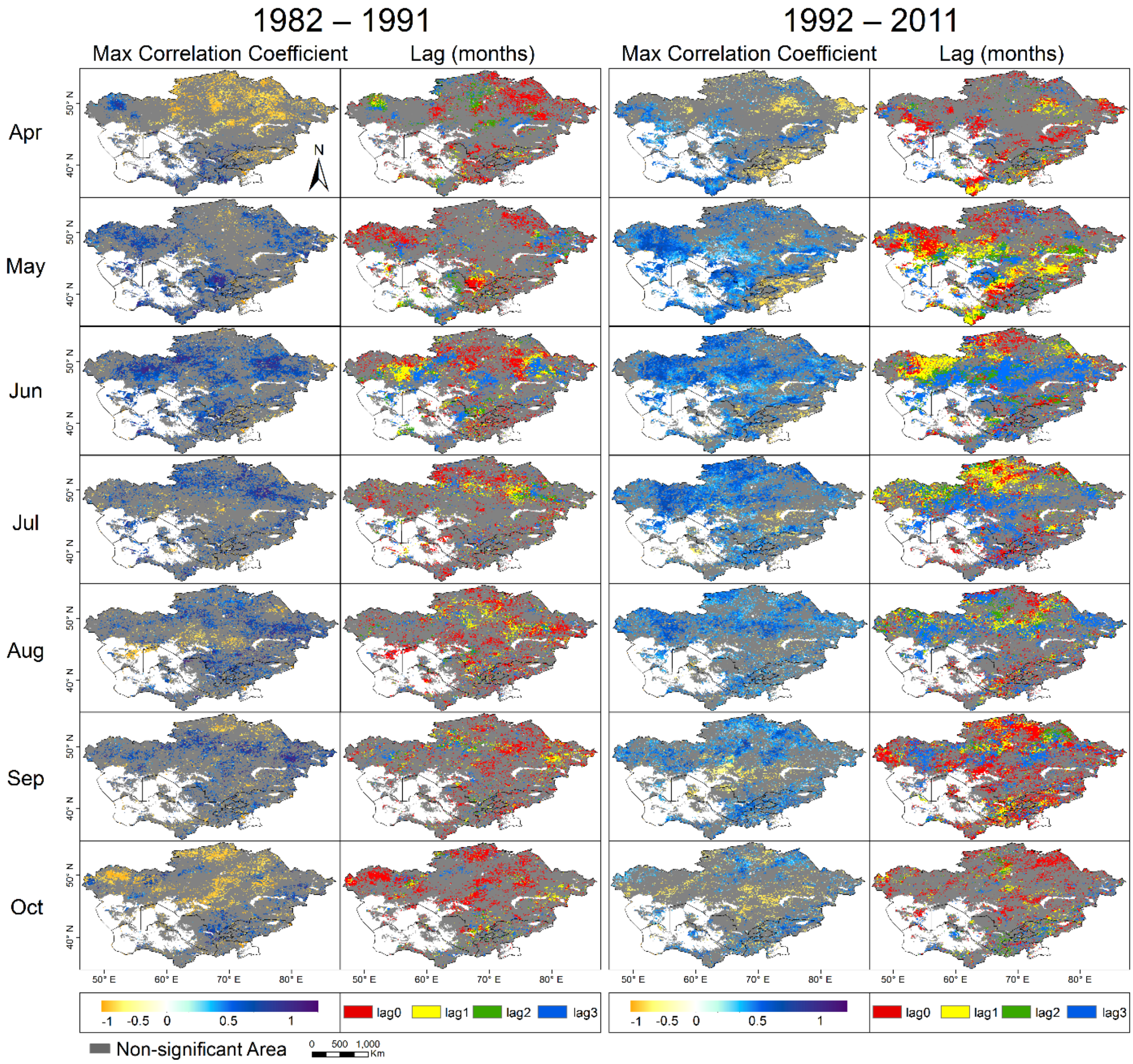

Figure 8. Lagged NDVI response to precipitation during 1982–1991 and 1992–2011. Maximum r corresponds to the maximum correlation coefficient for all correlation analyses between NDVI and precipitation in Central Asia. The resulting temporal lag represents the best fit for all time-lag correlation analyses. Areas with non-significant correlations (p-value > 0.05) are shown in dark gray.

The analysis, including the lagged months, revealed that the vegetation greenness was significantly (p-value < 0.05) affected by precipitation without a time lag (lag 0) for most areas in 1982–1991, accounting for nearly 20% of all vegetated areas in April–October (Figure 9a). Plants with a 1–3 month lag were mainly located in the central grasslands and southern shrublands in June. However, in 1992–2011, over 25% vegetated areas were characterized by a time lag of 1–3 months in May–September (Figure 9b).

Overall, the degree and time lag of the responses of the vegetation to precipitation were significantly different for the two periods. Considering the non-significant trends for precipitation in 1982–2011 (Table 1), it is reasonable to conclude that the observed change in the lagged response might mainly result from changes in the plant species or other disturbances.

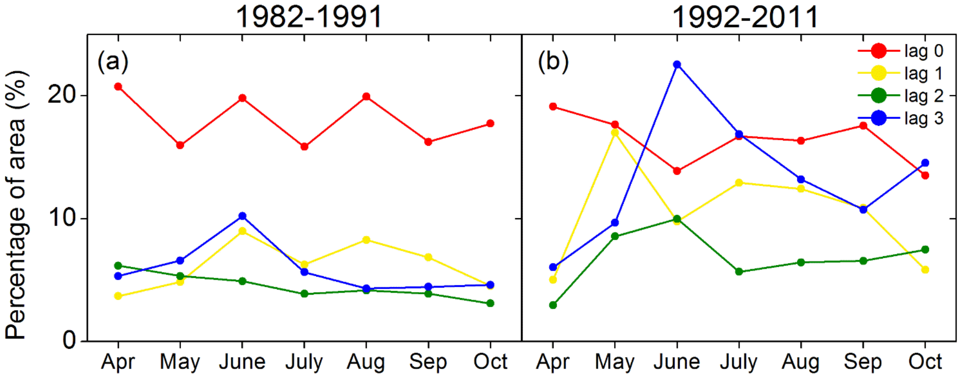

Figure 9. Percentage of vegetated area characterized by 0-month lag (red), 1-month lag (yellow), 2-month lag (green), and 3-month lag (blue) during (**a**) 1982–1991 and (**b**) 1992–2011 in NDVI response to precipitation (p-value < 0.05).

4. Discussion

4.1. Vegetation Variations and Their Relationships with Climatic Factors

In a study of Eurasia, Piao *et al.* [5] pointed out that a turning point for the NDVI in Central Asia mostly spanned from 1992 to 1996. In our study, the turning point in NDVI was given as the collapse of USSR in late 1991, with specific implications in the vegetation greenness pre- and post-1992. Before 1992, the NDVI displayed increasing trends for most Central Asia. However, decreasing trends in the vegetation greenness were detected for 22.9% of the vegetated areas after 1991. This coupling between vegetation trends and socio-economic conditions is in agreement with De Beurs *et al.* [44], and Lioubimtseva and Henebry [11].

According to our results, temperature had different impacts on greenness in 1982–1991 and 1992–2011(Figure 7). For 1982–2011, our study showed a consistently warming trend for Central Asia especially in 1992–2011, in agreement with previous studies [11,13]. For 1982–1991, our results demonstrated an enhancement in the vegetation greenness due to the warming trend, as warmer conditions during the early and late growing season are typically associated with lower levels of frost damage and overall better conditions for plant growth [42,45,46]. This is consistent with other results from high-latitude areas in Eurasia, North America, and China showing that a warming trend promotes greening [47–51]. However, as the warming trend significantly increased in 1992–2011, the increasing temperatures might have caused a larger water deficit due to evapotranspiration losses both annually and seasonally, thereby increasing the plant water stress and desiccation and impacting the rates of carbon uptake by photosynthesis [52–54]. Since the greenness decline observed in summer and autumn largely contributed to the annual decrease, it is likely that the extremely high temperatures for these two seasons were the main reason for the decrease in greenness in Central Asia in 1992–2011.

In addition, high temperatures are also a main cause of intense fire activities in this region that reduced vegetation greenness abruptly. Loboda *et al.* [3] used MODIS global fire data to characterize fire occurrence in Central Asia, and reported that the majority of burned areas in 2001–2009 corresponded to grasslands, especially in Kazakhstan [55]. In addition, the majority of burned areas resulted from late summer and autumn fires when the herbaceous biomass entered the senescence phase, contributing to a negative impact on greenn1ess. This further supports our findings that a warming climate is a crucial factor for vegetation greenness changes by aggravating water shortage and fire occurrence in Central Asia.

In 1982–2011, the annual precipitation generally positively correlated to annual NDVI (Figure 7). However, in April and October, the precipitation was negatively correlated with vegetation growth (Figure 8). This is contradicted to the common understanding in many other dryland areas (e.g., Africa [56], Australia [57]), where precipitation is a pivotal factor promoting greenness. One reason may be that the temperature in April and October in Central Asia is extremely low and the rainfalls in such low temperature easily form ice crystals in plant tissue, thus leading to the death of the plant, or at least damage to burgeon and young leaves [58]. Another reason may be that the excessive rainfall may have contributed to the formation of seasonally frozen soil. When soil is frozen, its thermal conductivity increases and its heat capacity decreases [59], which could significantly suppress vegetation growth.

Although the annual precipitation failed to demonstrate an accurate relationship with simultaneous vegetation greenness, the lagged correlation analyses revealed an important response of the vegetation to precipitation in Central Asia. This lagged phenomenon is also common in other dryland regions, such as Africa [60], northeast China [61], and the Great Plains [62]. Comparing the lagged response of the two periods, our study showed a time lag of 0 months for 1982–1991, but 1–3 months after 1992, especially for the grasslands of Kazakhstan. The time-lag mechanism of plant is controlled by plant root system that is capable of holding a large amount of moisture and transforms to shoots and leaves gradually [63,64]. Comparing to vegetation with less developed root systems, vegetation with strong root systems could avoid being immediately affected by precipitation shortage in the dry season. Thus, this prolonged lagged response during 1992 and 2011 showed a reinforcement of the plants root growth to strengthen their water-holding capability, indicating a transition in vegetation functional types as vegetation adapted to climate changes [63,65–67] in Central Asia.

4.2. Potential Impacts of the USSR Collapse on Climate-Vegetation Relationships

Our study proved that the correlation between climate and vegetation tended to be weaker in most northern parts of Kazakhstan during the post-USSR collapse period (Figure 7). Considering the Central Asian countries experienced large changes in land-use followed by socio-economic disturbance after the USSR collapse (e.g., wars, revolutions, policy changes, and economic crises) [68], these socio-economic factors are also likely to have contributed to the greenness changes, providing specific explanations for the change of climate-vegetation relationships in these regions.

During the socialist period of the USSR, northern Kazakhstan was characterized by rain-fed farmlands, accounting for 94% of the croplands in Kazakhstan in 1991–1993 [69]. This region was known as “the major granary” of the USSR and was heavily subsidized and intensified for farming [70,71], which may have been another reason for the increasing greenness in 1982–1991, apart from the climate contribution. However, comparing the regional NDVI trends for the five countries in Central Asia in 1992–2011, north Kazakhstan showed the largest decline in vegetation greenness for croplands (Figure 5(b)). During the post-USSR period, with the drastically reduced profitability of farming and unsecure land tenure, approximately three millions of people migrated outside of Kazakhstan in 1991–2006 [68,70,72]. Accordingly, millions of hectares of farmland were abandoned [22,23,73], leading to a considerable decrease in crop production in the 1990s [74], explaining the large decrease in cropland greenness in Kazakhstan (Figure 5). Due to these human disturbances, climate impact was much weaker on greenness in post-USSR period than that in pre- period in the northern Kazakhstan.

However, the climatic effects on greenness during the two periods in the Amu Darya and Syr Darya basins were completely different from that in the northern Kazakhstan. In the northern Kazakhstan, climate and vegetation had a strong correlation before 1991, and this correlation became weaker in 1992–2011. However, in the Amu Darya and Syr Darya basins, climate showed a weak correlation with vegetation greenness in 1982–1991, and became stronger after the USSR collapse (Figures 8 and 9). This can be explained by the different land-use policies or practices for the two periods in the Amu Darya and Syr Darya basins. Under the Soviet Union policy (and especially after the 1970s), the expansion of irrigated agriculture resulted in a 70% increase in irrigated farmlands in Central Asia [30]. In Uzbekistan, Turkmenistan, Tajikistan, and Kyrgyzstan, irrigation was the dominant agriculture practice for agriculture, accounting for 92%, 91%, 75%, and 67% of all croplands, respectively, in 1991–1993 [69]. Irrigation water supplement was the key factor to crop yield, therefore rainfall was less impacted on vegetation greenness during the pre-USSR collapse. However, the USSR intensified agriculture policies (e.g., expansion irrigation area; dam construction) caused environmental degradation (e.g., erosion, salinization, and decreasing fertility) in the Amu and Syr River basin [30,75,76]. Thus, after the USSR collapse, each country had to alleviate the environmental damage resultant from the over-extension of the irrigated area by rehabilitating the abandoned croplands [20,21] and plowing up the rain-fed crops in predominantly arid climate areas [19,77]. These actions led to a stronger dependency of plant growth on the climate variability during the post-USSR period, supporting our finding that the relationship between plants and rainfall became stronger in 1992–2011 for south Central Asian countries (*i.e.*, Uzbekistan) when the irrigated land area significantly decreased.

Human disturbance has a large impact on vegetation growth and its relationship with observed climate variations as findings in our study. According to the UNEP-WCMC [78], only 9% of the world’s drylands are nationally protected areas. Thus, to protect drylands, governments should also attach importance to the sustainable development of the dryland ecosystems by controlling socio-economic changes.

5. Conclusions

The main findings of our study can be summarized as follows:

1. The overall trends of NDVI evidently differed before and after 1992. The vegetation greenness showed an increasing trend for most areas before 1991, but experienced a dramatic decrease in 1992–2011.
2. Climate largely contributed to the greening/browning trends in Central Asia during these two periods, but its influence on greenness varied significantly. The increasing temperature

prompted vegetation greening before 1991 for most areas. However, in 1992–2011, this warming trend resulted in desiccation, suppressing the greening trend by increasing evapotranspiration and fire occurrences. The precipitation-controlled area expanded in 1992–2011, compared to 1982–1991. Moreover, the time-lag response of plants to precipitation extended to 1–3 months in 1992–2011.

3. Considering the distinctive greening/browning trends and their climatic responses during the pre- and post-USSR collapse, the effect of socio-economic changes on the climate-vegetation relationships cannot be ignored, such as the human migration in Kazakhstan and land-use policy changes in the Amu Darya and Syr Darya basins during the post-USSR period. Similar to vegetation greenness, these policy changes also had significant impacts on animals, with Bragina *et al.* [79] showing a rapid decline in large mammal populations in Russia, after the USSR collapse.
4. Our findings contributed to a comprehensive understanding of the role of climate change and its impact on drylands in Central Asia pre- and post-USSR collapse. Furthermore, our results provide an important illustration of the integrated effect of both climate variation and human disturbance on dryland vegetation growth. These findings will bring additional insight to the future response and adaptation of vegetation to climate change and human disturbance in the world's drylands.

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Author Contributions

Yu Zhou carried out and designed the research work, processed the data, analyzed and interpreted the results, and wrote the majority of the paper. Li Zhang supervised and designed the research, assisted with interpretation of the results and contributed to manuscript organization, writing and revisions. Rasmus Fensholt helped with discussions and manuscript revisions. Kun Wang and Feng Tian helped with discussions and part of data processing. Irina Vitkovskaya provided useful suggestions to result interpretations and helped with discussions.

Conflicts of Interest

The authors declare no conflict of interest.

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