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Key Points:

- NDVI of natural vegetation reversed to decline from increased trend since 1998
- Shrub encroachment into grassland cover occurred
- Intensified warming and diminished precipitation bring some negative ecological effects

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Potential impacts of climate change on vegetation dynamics in Central Asia

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Abstract Observations indicate that although average temperatures in Central Asia showed almost no increases from 1997 to 2013, they have been in a state of high variability. Despite the lack of a clear increasing trend, this 15 year period is still the hottest in nearly half a century. Precipitation in Central Asia remained relatively stable from 1960 to 1986 and then showed a sharp increase in 1987. Since the beginning of the 21st century, however, the increasing rate of precipitation has diminished. Dramatic changes in meteorological conditions could potentially have a strong impact on the region's natural ecosystems, as some significant changes have already occurred. Specifically, the normalized difference vegetation index (NDVI) of natural vegetation in Central Asia during 1982–2013 exhibited an increasing trend at a rate of 0.004 per decade prior to 1998, after which the trends reversed, and the NDVI decreased at a rate of 0.003 per decade. Moreover, our results indicate that shrub cover and patch size exhibited a significant increase in 2000–2013 compared to the 1980s–1990s, including shrub encroachment on grasslands. Over the past 10 years, 8% of grassland has converted to shrubland. Precipitation increased in the 1990s, providing favorable conditions for vegetation growth, but precipitation slightly reduced at the end of the 2000s. Meanwhile, warming intensified 0.93°C since 1997 compared to the average value in 1960–1997, causing less moisture to be available for vegetation growth in Central Asia.

1. Introduction

Vegetation activity is regarded as one of the most important indicators for evaluating interactions between climate and terrestrial ecosystems. Vegetation dynamics are highly sensitive to climate change, especially in arid and semiarid regions [*Sitch et al.*, 2003; *Acreman et al.*, 2009; *Wang et al.*, 2011]. Normalized difference vegetation index (NDVI) trends have been used for numerous purposes, including the assessment of ecological responses to global warming, crop status [*Tottrup and Rasmussen*, 2004], and desertification [*Jeong et al.*, 2011]. The monitoring of terrestrial vegetation dynamics thus underpins efforts to better understand the relational feedback between vegetation and the atmosphere [*Bounoua et al.*, 2010; *Angelini et al.*, 2011].

Despite the continued increase in atmospheric greenhouse gas concentrations, an apparent hiatus in the steady rise of average temperatures has occurred since about 1998, both globally and regionally [*Kosaka and Xie*, 2013; *Watanabe et al.*, 2013; *Meehl et al.*, 2011, 2014; *Chen and Tung*, 2014]. However, this 15 year period is still the warmest in nearly half a century in Central Asia. Following a sharp increase in 1997, the temperature has since been in state of high variability in Central Asia [*Foster and Rahmstorf*, 2011; *Chen et al.*, 2015]. Furthermore, pan evaporation reversed from a decline to a significant upward trend in arid zones [*Li et al.*, 2013b], which might have a strong potential impact on the region's natural ecosystems. For instance, plant transpiration and soil water consumption may increase in the plain desert area.

Central Asia is located in the hinterland of the Eurasian continent and has a unique landscape that features expansive but fragile mountain-oasis-desert ecosystems. It is one of the driest areas in the world [*Josef et al.*, 1997] and is characterized by low vegetation coverage. The vegetation that does survive in this zone is mainly dependent on soil water as well as shallow groundwater from precipitation and glacier/snowmelt water in the mountains.

The ecosystems in this system are intensely sensitive to global climate change [*Chen et al.*, 2009], and the rising temperatures and increased evaporation are accelerating the soil water consumption. This, coupled with a significant decline in water storage and shallow groundwater levels, is causing the shallow roots of desert plants to die. The subsequent reduction in species diversity and vegetation cover is rendering the

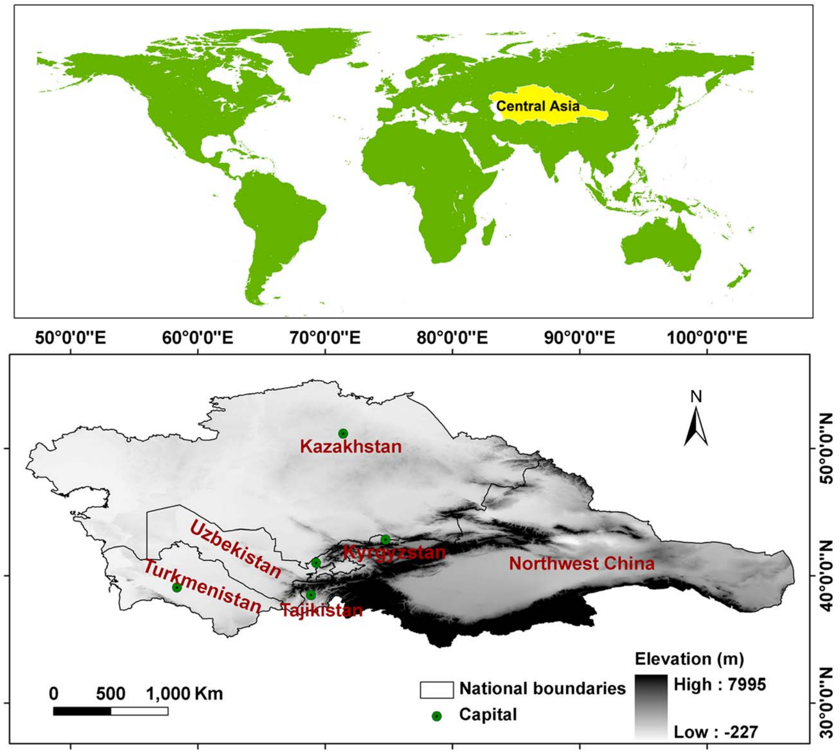

Figure 1. Sketch map of study area.

water-starved ecosystem increasingly fragile. Therefore, an investigation into vegetation dynamics, including the identification of vegetation response to hydroclimatic changes, is essential for coping with future climate change. In terms of overall water resources management, it is important to understand what has caused the greening or browning trends if we are to successfully manage or prevent them in the future.

2. Materials and Methods

2.1. Study Area

Central Asia consists of Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, Uzbekistan, and the arid region of Northwest China (Figure 1). It lies west of the Helan Mountains, east of the Caspian Sea and Volga River, and south of the Aral Sea and Irtysh River. The geomorphological patterns of the five countries in Central Asia are mainly desert and grasslands. However, the typical topography and geomorphology of the arid region of Northwest China includes towering glaciers, widespread deserts (e.g., the Gobi), vast grasslands, sporadic oases, and numerous mountains and basins. China's largest (and the world's second largest) mobile desert, the Taklimakan Desert, is located in the south central portion of the area. It contains the Karakum Desert, the Kyzylkum Desert, the Gurbantünggüt Desert, the Badain Jaran Desert, and the Tengger Desert. Almost all rivers in Central Asia are inland rivers.

Central Asia has a continental climate and is one of the most arid areas in the world. In addition to high amplitudes in the seasonal cycle of temperature, the conditions are semiarid to arid, with a persistent moisture deficit and low relative humidity. The Caspian Sea and Aral Sea do not attenuate these extreme conditions beyond the directly adjacent areas [*Lydolph*, 1977]. The ecological environment is fragile and unstable, and the species are extremely poor.

2.2. Data and Methods

The monthly 0.5° grid data of temperature Hadley Climatic Research Unit Temperature (HadCRUT) and precipitation series used in this study is from 1960 to 2013. The series was developed by the Climatic Research Unit (University of East Anglia) in conjunction with the Hadley Centre (at the UK Met Office). The monthly mean Palmer Drought Severity Index (PDSI) provides a measurement of surface moisture conditions (2.5° grid spatial resolution) from 1982 to 2013 and is available at http://www.cgd.ucar.edu/cas/catalog/climind/pdsi.html. Global very dry areas are defined as $\text{PDSI} < -3.0$, while very wet areas are defined as $\text{PDSI} > +3.0$ [*Dai et al.*, 2004].

The soil moisture data, net longwave radiation, net shortwave radiation, and surface specific humidity come from the Global Land Data Assimilation System (GLDAS). The GLDAS data set was validated against available data from multiple sources [*Zhang et al.*, 2008; *Chen et al.*, 2013]. In this study, we used GLDAS-2 data (NOAH Model, 0.25 × 0.25°) for the period 1960–2010, and GLDAS-1 data (NOAH Model, 0.25 × 0.25°) for the period 2001–2013. We established a linear relationship model using data from the overlap period 2001–2010 and then estimated and extended the GLDAS-2.0 series using the relational expression to maintain the consistency of the data series. The depths of the four soil layers range from 0 to 10, 10 to 40, 40 to 100, and 100 to 200 cm.

The normalized difference vegetation index (NDVI) data of Advanced Very High Resolution Radiometer from 1982 to 2006 were collected from the Global Inventor Modeling and Mapping Studies (GIMMS) group at a spatial resolution of 8 × 8 km and a 15 day temporal resolution, along with Moderate Resolution Imaging Spectroradiometer (MODIS) data from 2001 to 2013 from the University of Maryland (UMD). To match the GIMMS data, MODIS data at a resolution of 1 km × 1 km were resampled to a resolution of 8 km × 8 km. The research used a per pixel unary linear regression model in the overlap period to integrate different sensor data and then applied the Maximum Value Composites method to synthesize monthly and annual data. We utilized the NDVI values of natural vegetation to represent the responses of local vegetative conditions to climate change.

On a global scale, several research organizations have constructed multiple land use and land cover classification systems over the years for different purposes. Although these classification results cannot be directly compared, we can obtain an integrated classification of land use/cover change based on a feature fusion process from the different data sets. The feature fusion process is often used to achieve combined characteristic information through the single feature extraction process, in order to get comprehensive information. Using the process, we can reanalyze these data to obtain macroscopic characteristics and land use/cover change trends. Due to the lack of systematic information on changes in land use/cover change, this study utilized UMD data for the 1980s, Global Land Cover Characteristics data from the International Geosphere-Biosphere Program for 1992, and MODIS data for 2000 and 2013.

1. The elementary structure form of the model for the different data is as follows:

$$Gi = a + bVi + ei \tag{1}$$

$$a = \overline{G} - b\overline{V} \tag{2}$$

$$b = \frac{\sum_{i=1}^{n}\left(Gi - \overline{V}\right)\left(Gi - \overline{G}\right)}{\sum_{i=1}^{n}\left(Vi - \overline{V}\right)^2} \tag{3}$$

   G_i represents GIMMS NDVI in the *i*th month, V_i is MODIS NDVI (8 km × 8 km) in the *i*th month, ε is random error, $\overline{G}$ is the mean of all monthly GIMMS data from 2001 to 2006 at the corresponding pixels, and $\overline{V}$ is the mean of all MODIS NDVI data (8 km × 8 km) from 2001 to 2006 at the corresponding pixels.

2. *Trend analysis*. To further investigate the trends of yearly maximum NDVI, the linear trends from 1982 to 1998 and 1998 to 2013 were examined on a per pixel basis. Linear trend estimation is used to establish a linear regression relationship between variables (x_i) and time (t_i). The regression coefficient (b) represents a trend of variable (x_i)

$$b = \frac{n \times \sum_{i=1}^{n} xiti - \sum_{i=1}^{n} xi \sum_{i=1}^{n} ti}{n \times \sum_{i=1}^{n} ti^2 - \left(\sum_{i=1}^{n} ti\right)^2} \tag{4}$$

3. *Partial correlation analysis*. Partial correlation analysis is a method used to describe the relationship between two variables while taking away the effects of another variable or of several other variables. Each partial

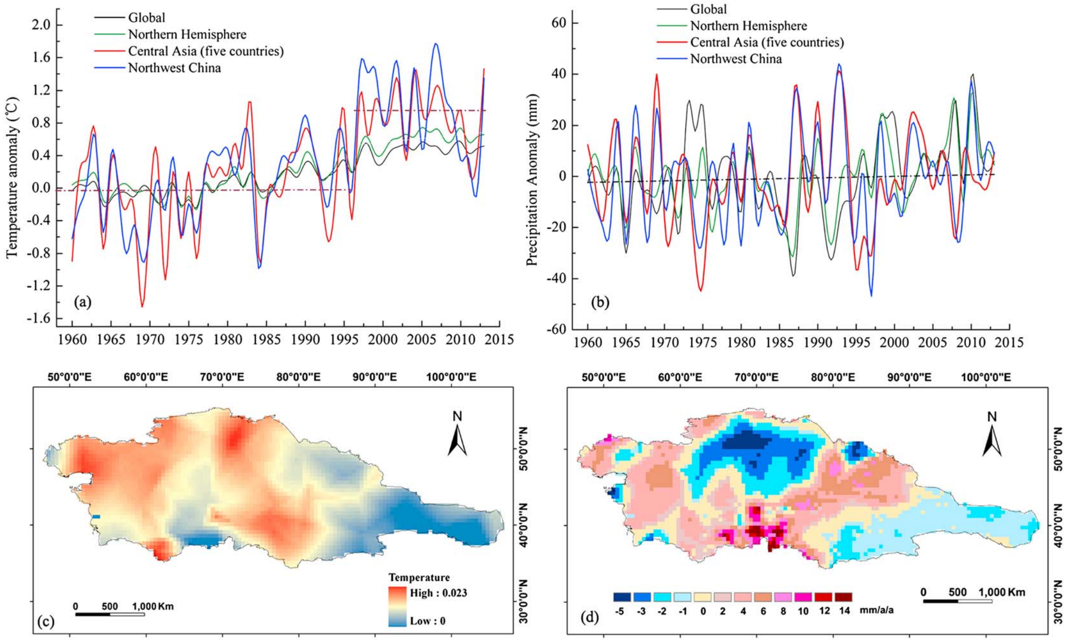

Figure 2. Temporal and spatial changes of temperature and precipitation during 1960–2013. (a) Annual temperature anomaly and (b) annual precipitation of Global, Northern Hemisphere, Central Asia (five countries), and arid region of Northwest China; (c) trend of temperature and (d) trend of precipitation (mm/a/a) in Central Asia (including Northwest China).

correlation coefficient is tested using the *t* test at a significance level of 0.05. The partial correlation of x_1 and x_2 is adjusted for a third variable, *y*

$$r_{x1x2\cdot y} = \frac{r_{x1x2} - r_{x1y}r_{x2y}}{\sqrt{\left(1 - {r_{x1y}}^2\right)\left(1 - {r_{x2y}}^2\right)}} \tag{5}$$

3. Results

3.1. Changes in Temperature and Precipitation

From 1960 to 2013, average annual temperatures worldwide, as well in the Northern Hemisphere, Central Asia (five countries), and the arid region of Northwest China, all experienced a significant increasing trend. The warming trend began to accelerate from the late 1970s onward, with each decade growing warmer than the previous ones. The trend experienced a sharp increase in 1997, making the 15 year time frame from 1997 to 2013 the warmest period in the last half-century (Figure 2a). The spatial distribution of temperature trends from 1960 to 2013 shows that the areas of accelerated warming are mainly in northern and western Kazakhstan (Figure 2c).

Also in the 1960 to 2013 time frame, precipitation in Central Asia showed an overall slightly increasing trend. However, the decadal fluctuation amplitude was greater in Central Asia than the overall level globally or in the Northern Hemisphere. In 1960–1986, precipitation levels remained relatively stable, but they then started to increase in 1987 at a rate of 7.8 mm/a. The 1990s were the most humid decade in the past half-century in Central Asia, but unlike the continuously increasing trends of precipitation in global and Northern Hemisphere, Central Asian precipitation showed a slight downward trend from 2000 to 2013 (Figure 2b). The spatial distribution of precipitation trends in 1960–2013 shows that the most significantly reduced area was northern Kazakhstan (Figure 2d).

3.2. Response of Soil Moisture to Climate Change

Soil moisture reflects surface hydrological processes and is an important indicator for measuring wetness and dryness levels. Furthermore, soil moisture not only directly responds to precipitation but is also controlled by changes in temperature and radiation. Thus, spatial and temporal variations in soil moisture are closely

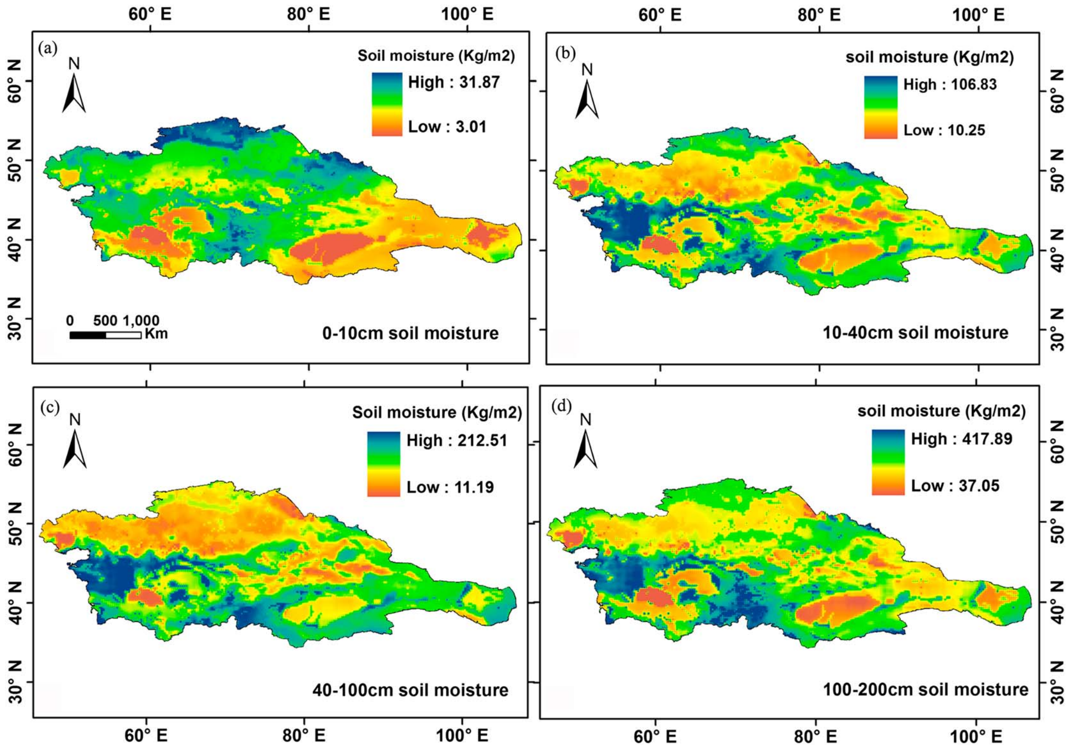

Figure 3. (a–d) Average soil moisture in different layers in 1960–2013.

related to the ecosystem [*Davis and Pelsor*, 2001; *Yang et al.*, 2010]. The different layers of average soil moisture in Central Asia during 1960–2013 showed that Northwestern China and Turkmenistan have less soil moisture in shallow soil layers, and Kazakhstan has much more. This is especially obvious in the 0–10 cm soil layer (Figure 3a). In deep soil layers, the soil moisture in Kazakhstan is low and does not increase with depth (Figures 3c and 3d).

Soil moisture at different depth layers correlates with temperature, precipitation, humidity, and radiation changes. Changes related to climatic factors have the largest impacts on shallow soil layers (0–10 cm) (Table 1), with precipitation being the most important factor influencing soil moisture. The dryness and wetness of soil moisture are almost the same as the dryness and wetness of climate. Other meteorological factors such as air temperature and solar irradiation have some influence on soil moisture, but air humidity has a negative correlation with radiation. Temperature and solar radiation cause soil moisture loss mainly through evapotranspiration (ET).

Average soil moisture is low in arid and semiarid regions. These areas are usually rich in solar energy resources and receive more sunlight than other ecosystems, resulting in an annual evapotranspiration greater than the annual precipitation. Evapotranspiration thus becomes the key process of soil moisture loss. The temporal and spatial variability of soil moisture is the result of integrated influences of warming, precipitation, increased solar radiation, and decreased surface specific humidity.

Table 1. Relations (Pearson Correlation) of Average Soil Moisture Between Temperature, Precipitation, Radiation, and Humidity in Central Asia in 1960–2013

Soil Moisture	Temperature	Precipitation	Net Radiation	Surface Humidity
0–10 cm	−0.29	0.64**	−0.30	0.43*
10–40 cm	−0.02	0.59*	−0.26	0.28
40–100 cm	−0.13	0.46*	−0.16	0.35
100–200 cm	−0.24	0.24	−0.03	0.31

*Significant at 0.05 level.
**Significant at 0.01 level.

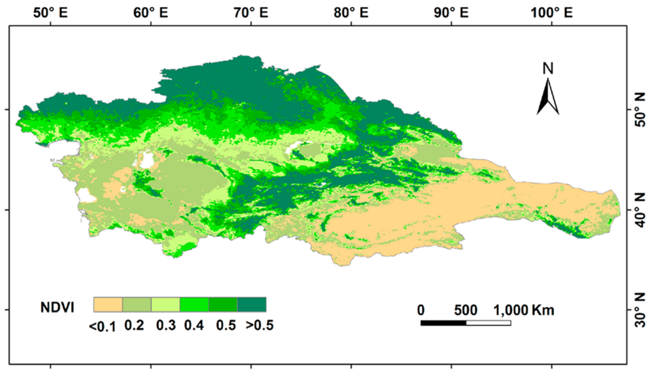

Figure 4. Distribution of average NDVI in Central Asia in 1982–2013.

Sparse vegetation cover is the main environmental characteristic of arid areas. Plants with this type of growth mainly depend on shallow soil water and shallow groundwater to survive. Climate change increases soil water loss, causing the shallow roots of desert plants to die. The process intensifies desertification and also leads to water-based ecosystems becoming significantly more fragile in arid regions.

3.3. Ecological Effects of Recent Climate Change

A water-based ecosystem is extremely fragile in an arid or semiarid region, making it highly sensitive to climate change and human activities [*Lioubimtseva*, 2004]. Changes in hydrothermal conditions directly affect the growth of vegetation, while rising temperatures exacerbate the degeneration of the ecosystem and intensify the desertification process.

3.3.1. Reversing the Ecological Effects of Climate Change

Vegetation in Central Asia is generally characterized by desert vegetation mixed with mountains and oases vegetation patches. The monthly maximum NDVI values were calculated using the maximum value composite. Due to the impact of westerly circulation, vegetation in the northwestern region of Central Asia is less sparse than that in the southeastern region (Figure 4). The transport path of westerly circulation moves from west to east, so the overall NDVI tends to decrease. This trend reflects the vegetation's response to the moisture gradient.

On a latitude distribution, vegetation in Central Asia is characterized by higher NDVI in the northern part and lower NDVI in the southern part. The spatial distribution of average NDVI shows that the areas of high vegetation coverage are mainly in northern Kazakhstan, the Ili River Valley, the Altay region, and the Qilian Mountains in Northwest China, while the areas of low vegetation coverage are mainly in the Tarim Basin in Xinjiang and the Gobi Desert area in the Hexi Corridor. This is mainly because there is less precipitation and glacier/snow meltwater in these areas. Tajikistan and Kyrgyzstan have mountains as their main characteristic and thus have a relatively small desert area.

The demarcation point of 0.1 was identified as a general threshold to distinguish vegetated from unvegetated areas [*Zhou et al.*, 2001; *Fang et al.*, 2003; *Iwsaki*, 2006]. Furthermore, cultivated land was excluded when obtaining the series of NDVI values of natural vegetation from 1982 to 2013. The NDVI variation of natural vegetation in the natural growing season (April–October) during the 1982–2013 time frame is shown in Figure 5. Here we see that the average vegetation index presented in two-stage changes. In the first stage, the NDVI of natural vegetation showed an increasing trend from 1982 to 1998. However, this trend reversed in 1998, with the degradation range showing as smaller than the previous enhanced range. In the period 1982–1998, the NDVI increased at a rate of 0.004 per decade, whereas in 1999–2013, the NDVI decreased at a rate of 0.003 per decade.

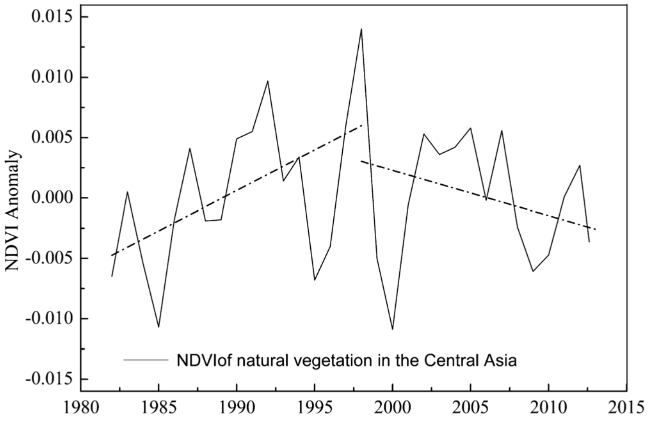

Figure 5. Change in annual NDVI of natural vegetation in Central Asia in 1982–2013.

The NDVI variation trend indicates that vegetation degradation mainly occurred in northern Kazakhstan, east of the Aral Sea, around Balkhash Lake, and in the northern Altai region. Moreover, the NDVI also showed decreasing trends in the valley bottom of Kyrgyzstan, southern Turkmenistan, the central Tianshan Mountains, and the southern slope of the Altai Mountains. Stable vegetation tended to experience an increasing trend mainly in eastern Balkhash Lake, southwest of Kazakhstan, and south of the Junggar Basin (Figures 6a and 6b).

3.3.2. Integrated Effects of Hydrothermal Conditions on NDVI

The hydrothermal conditions of vegetation in arid regions mainly depend on temperature and precipitation changes. According to partial correlation analysis, the partial correlation coefficients of NDVI between temperature and precipitation prior to 1998 are 0.27 and 0.69 (exceeding the 0.01 confidence level), respectively. However, after 1998, the partial correlation coefficients of NDVI between temperature and precipitation are −0.2 and 0.4, respectively. Consistent significantly decreasing precipitation in northern Kazakhstan is the main factor leading to notable NDVI decreases in this region, whereas the temperature maintains positive magnitude changes throughout the entire period (Figures 6c–6f).

Accelerating glacier melt, driven by rising temperatures, caused an increase in runoff from mountain catchments. These catchments form the major water source replenishing the soil water stored in most of the oases. However, regions with even higher negative correlations are scattered throughout the lower reaches, where the riparian vegetation is under high temperature and aridity stress. The PDSI, which integrates precipitation and temperature as a measurement of surface moisture conditions, decreased in 1998–2013 (Figures 6g and 6h). This indicates a growing aridity in Central Asia. Hence, the negative effects of climate change on the ecology of the arid desert region are likewise growing.

Climate change is the driving factor of natural vegetation dynamics. Hydrothermal changes in Central Asia clearly show a staged change as well as NDVI variations in natural vegetation. The NDVI of natural vegetation increased with rises in heat and water levels prior to 1998; however, the high variability in temperature has led to the decrease of PDSI and the degradation of natural vegetation since that time.

3.3.3. Shrub Encroachment Into Grassland

Shrub encroachment usually results in a mosaic landscape, with shrub patches interspaced with grass patches. This is defined as shrub-encroached grassland [*Chen et al*., 2014]. Shrub encroachment into grassland and the thickening of woody plant cover in savannas are widely reported in arid and semiarid areas [*Knapp et al*., 2008; *Maestre et al*., 2009]. Shrub cover and patch sizes were greater in dry and warm habitats than in moist and cool sites [*Chen et al*., 2014; *Li et al*., 2013a]. Shrub encroachment is the result of many interrelated factors influencing each other in multiple spatial and temporal scales. Climate is a major factor influencing the structural measurements of shrub-encroached grassland [*Chen et al*., 2014].

Based on the land use/cover classification data from the past 30 years, land use in Central Asia has experienced considerable changes, especially in the last decade. Most notable among these changes are the phenomena of grassland degradation, forest reduction, cultivated land expansion, and shrub encroachment. The grasslands in northern Kazakhstan have been dramatically reduced, and the open shrublands in Uzbekistan, Turkmenistan, and the Tarim River Basin in Northwest China have increased substantially, highlighting shrub encroachment into grassland (Figure 7). These regions are characterized by high variability warming and shallow soil moisture. The warming accelerates the evapotranspiration of the shallow soil layer.

Based on the matrices method in ArcGIS software, we analyzed the conversions of the land use/cover changes. The results indicated that the grassland decreased by about 25.9%, and open shrubland increased by about 13.5%. Furthermore, during the 2000–2013 time frame, about 8% of grassland was converted to shrubland, and 9.9% of forest land was converted to shrubland. Shrub encroachment into native grasslands alters species interaction, which in turn may promote a loss of biodiversity and influence various aspects of ecosystem functioning. While shrub encroachment is not equated with desertification, vulnerable terrestrial ecosystems are generally thought to be highly susceptible to degradation and desertification caused by climatic fluctuations.

4. Discussion

Due to the lack of systematic and consistent information, this study used the land use/cover change data from different available sources, as all of them can characterize the situation at some point in time. This study helps fill in the information gap in Central Asia, such that it basically reflects the macroscopic evolution characteristics of the land pattern.

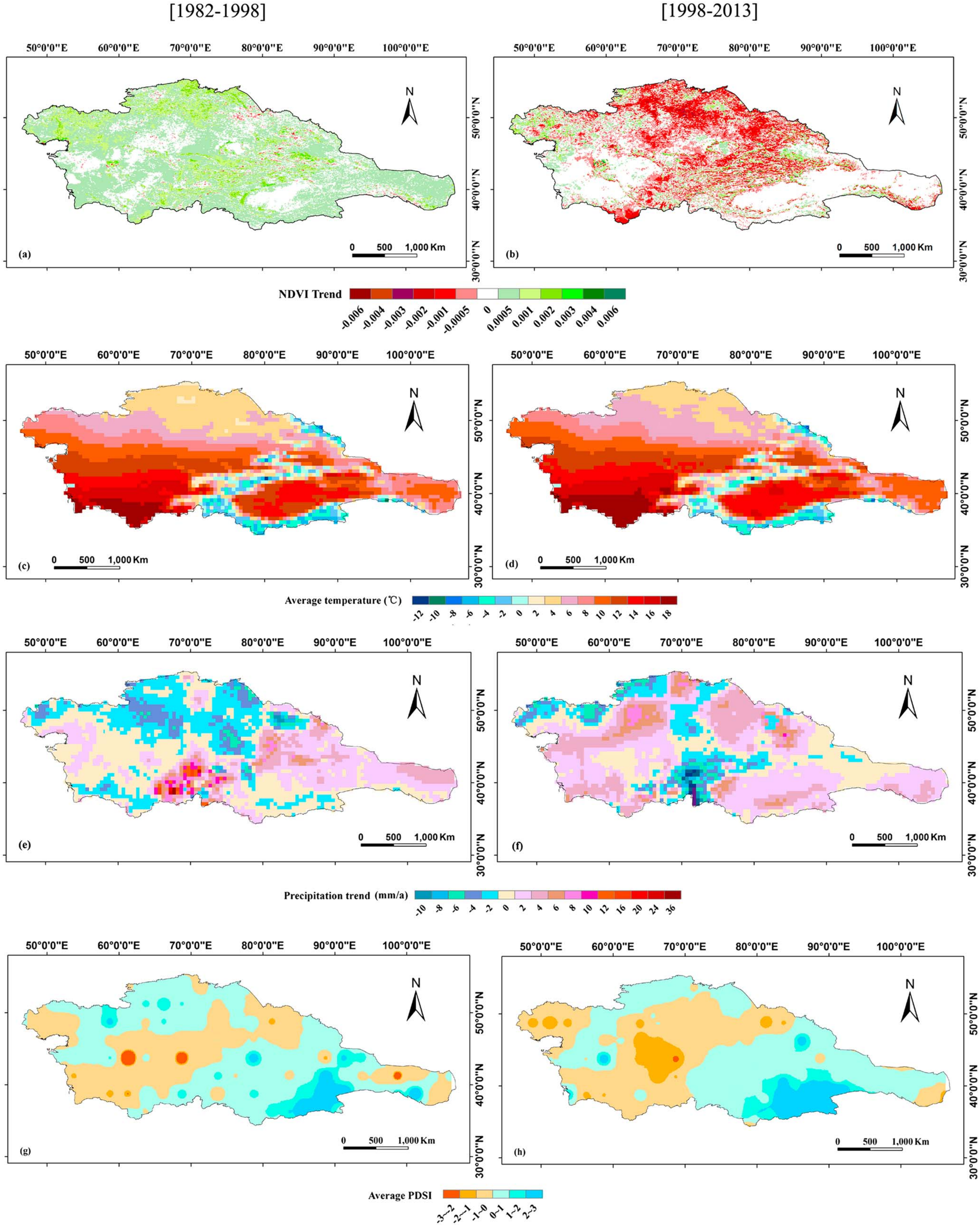

Figure 6. Spatial distributions of the average growing season (a and b) NDVI of natural vegetation, (c and d) average temperature, (e and f) precipitation trend, and (g and h) PDSI for the periods 1982–1998 and 1998–2013 in Central Asia.

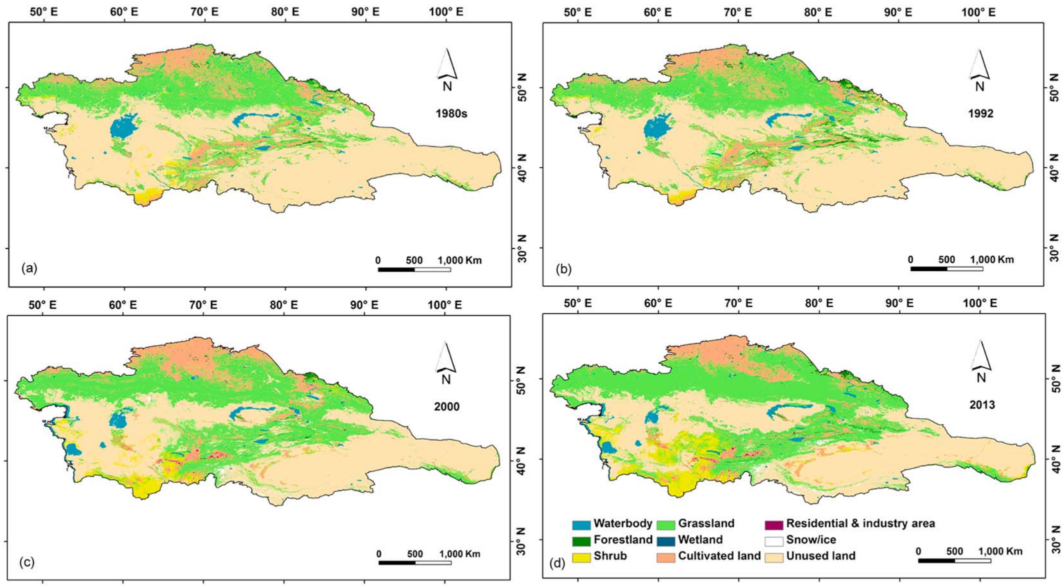

Figure 7. Land use/cover change in Central Asia in the (a) 1980s, (b) 1992, (c) 2000, and (d) 2013.

The vegetation in Central Asia generally contains two types of plants: the mesophyte plant, whose main water source is precipitation, and the xerophilous plant, whose main water source is groundwater and runoff from mountain areas. The phenomenon of shrub encroachment implies that some mesophyte plants are turning into xerophilous plants, which will lead to the water-based ecosystem becoming much more fragile in Central Asia. Furthermore, the spatial pattern of vegetation cover is dually controlled by both water and heat, but especially water. The slightly reduced precipitation and enhanced warming in recent decades indicates that, under continuous warming, the moisture supply related to precipitation may modulate the vegetation growth in that region.

Consistent with previous studies [*Hill and Donald*, 2003; *Beck et al.*, 2011; *Wang et al.*, 2014], our results showed that climate is a major factor influencing the large-scale patterns of community structure and ecological attributes. Water is the limiting factor for ecological attributes in arid and semiarid areas, and vegetation dynamics are highly sensitive to alterations in water availability. This indicates that water conveyance is necessary for protecting important vulnerable ecological regions [*Chen et al.*, 2014].

Recent studies showed that soil, carbon dioxide concentration, and human activities (e.g., land use/cover change and grazing) were also considered important aspects that affect natural vegetation changes such as shrub encroachment [*Jackson et al.*, 2002; *Eldridge et al.*, 2011; *Cipriotti et al.*, 2012]. These factors are interrelated and influence each other in multiple spatial and temporal scales (Figure 8). Although precipitation showed an overall increasing trend in the past half-century, the increases in warming have outpaced increases in precipitation. Such changes have already produced significant impacts. Accelerating glacier melt caused by rising temperatures led to an increase in runoff, which brought ecological benefits. In contrast, the decrease in soil moisture caused by increased evapotranspiration (ET), driven by rising temperature and radiation, produced negative ecological impacts.

Previous studies showed that climate is the major factor influencing the large-scale patterns of community structure and ecological attributes in grassland and savanna ecosystems [*Bai et al.*, 2008; *Chen et al.*, 2014], and that grazing does not necessarily lead to shrub encroachment on grassland [*Oliva et al.*, 1998; *Jones and Bunch*, 1999]. The process also depends on the local climate, soil, and other nonbiological factors.

In northwestern China, the northern slope economic zones of the Tianshan Mountains, including the Ili River Basin, are livestock industrial areas (Figure 8). This region has abundant water resources, so shrub encroachment is less obvious there than in the Tarim River Basin near the edges of the Taklimakan Desert (which is not a core grazing region). Over the past three decades, shrub areas have increased by 1.68 times in the Tarim River Basin, but there is no obvious change in the northern slope economic zone of the Tianshan Mountains.

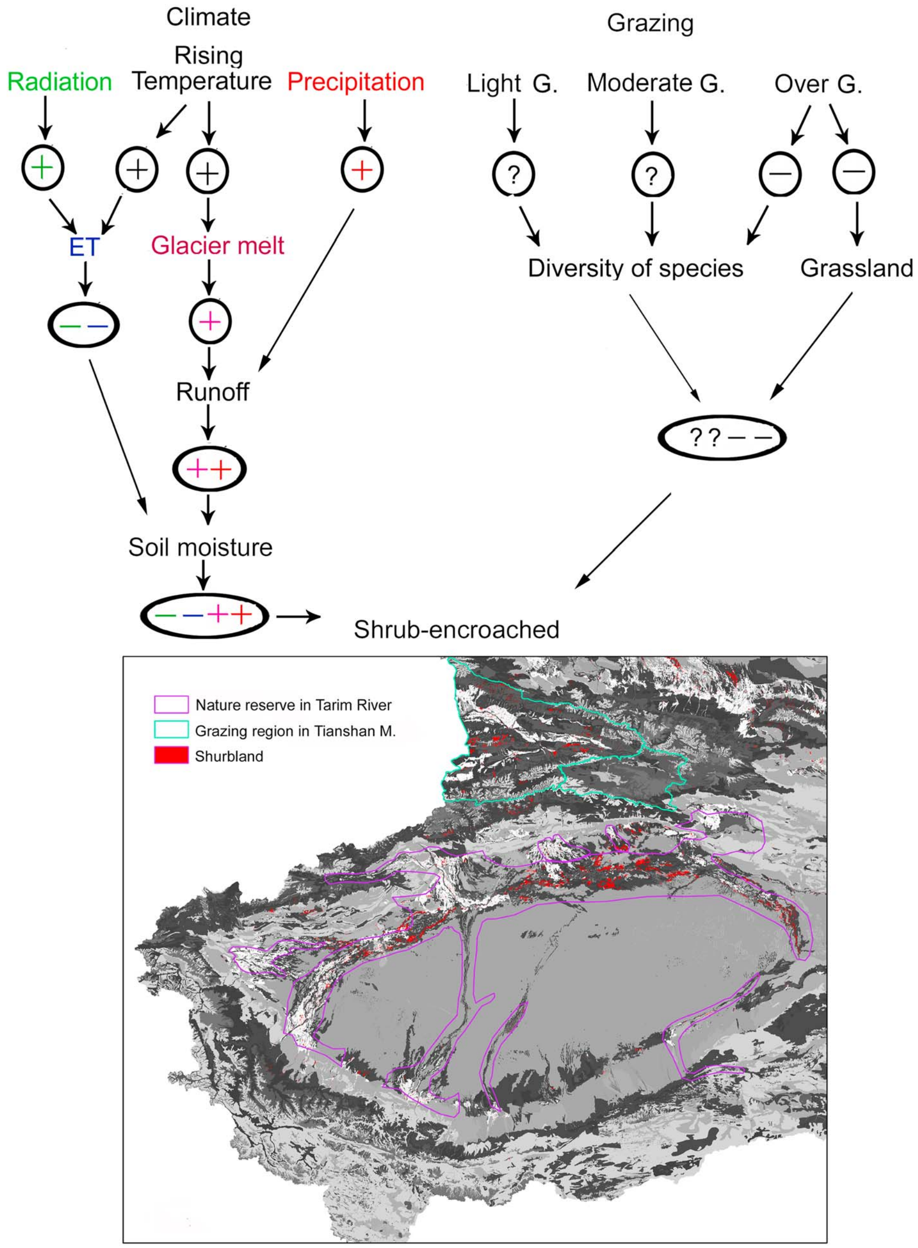

Figure 8. Schematic diagram of the combined effects of climate change and human activities on shrub-encroached grasslands in Central Asia.

In some cases, livestock grazing has had no significant effect on plant genetic diversity. However, in continuous overgrazing situations, a negative relationship between genetic diversity and grazing was observed and resulted in reduced plant population size [*Ma et al.*, 2014]. Although there are grazing prohibitions in Central Asia on the large-scale natural grasslands of Nalati, Tianchi, and Bayinbuluke, etc., some herdsmen settlements and livestock populations are still growing in some areas, and are thus having negative impacts on vegetation diversity arid grazing ecosystems. This has led to serious degradation in grasslands.

Furthermore, previous studies reported the possible influence of vegetation feedback on climate change [*Jeong et al.*, 2010]. Vegetation greenness is thought to be a major factor that alters surface atmospheric conditions by directly affecting surface albedo, emissivity, and soil moisture content, as well as altering latent and sensible heat fluxes [*Xue*, 1997]. These concerns will be the subject of follow-up studies. The response of arid ecosystems to climate change and water alterations should receive particular attention.

5. Conclusions

In this paper, we have studied long-term vegetation dynamics and the response of vegetation to hydroclimatic changes in Central Asia, a typical arid region with vulnerable ecosystems.

1. Vegetation dynamics are extremely sensitive to climate change, especially in arid regions. The NDVI of natural vegetation during 1982–2013 in Central Asia exhibited an increasing trend at a rate of 0.004 per decade prior to 1998, after which the NDVI trends reversed and started to decrease at a rate of 0.003 per decade. The most obvious NDVI decline occurred in northern Kazakhstan.
2. Shrub encroachment in grasslands generally leads to a mosaic landscape that features shrub patches interspaced with grass patches. Shrub encroachment into grassland cover in Central Asia has recently occurred. Shrubland increased most significantly in Uzbekistan, Turkmenistan, and the Tarim Basin in Northwest China over the past 10 years, implying that some mesophyte plants are turning into xerophilous plants. Moreover, in the vast desert area of Central Asia, recent dynamic climate changes are causing the shallow roots of desert plants to retreat and die.
3. The temperature in Central Asia experienced a sharp increase in 1997 and has been in a state of high variability since then. The precipitation trend showed an increase in 1987, but this diminished in the early 21st century. It has been suggested that the increase in precipitation and global (or regional) warming resulted in atmospheric conditions that were suitable for vegetation growth in Central Asia during the 1990s. However, intensified warming and slightly decreased precipitation caused increased negative PDSI in surface moisture conditions during 1998–2013. These changes point to a further increase in aridity in Central Asia. Climate, especially precipitation, is the major factor influencing large-scale patterns of community structure and ecological attributes.

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