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RESEARCH ARTICLE

# Satellite-indicated long-term vegetation changes and their drivers on the Mongolian Plateau

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**Abstract** The Mongolian Plateau, comprising the nation of Mongolia and the Inner Mongolia Autonomous Region of China, has been influenced by significant climatic changes and intensive human activities. Previous satellite-based analyses have suggested an increasing tendency in the vegetation cover over recent decades. However, several ground-based observations have indicated a decline in vegetation production. This study aimed to explore long-term changes in vegetation greenness and land surface phenology in relation to changes in temperature and precipitation on the Plateau between 1982 and 2011 using the normalized difference vegetation index (NDVI). Across the Plateau, a significantly positive trend in the growing season (May–September) NDVI was observed from 1982 to 1998, but since that time, the NDVI has not shown a persistent increase, thus causing an insignificant trend over the entire study period. For the steppe vegetation (a major vegetation type on the Plateau), the NDVI increased significantly in spring but decreased in summer. Precipitation was the dominant factor related to changes in steppe vegetation. Warming in spring contributed to earlier vegetation green-up only in meadow steppe vegetation, implying that water deficiency in typical and desert steppe vegetation may eliminate the effect of warming. Our results also suggest a combined effect of climatic and non-climatic factors and highlight the need to examine the role of regional human activities in the control of vegetation dynamics.

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## Introduction

The Mongolian Plateau, a major component of the Eurasian Steppe, plays an important role in regulating biospheric feedbacks to climate change (Hall et al. 1995). Thus, timely and accurate monitoring of vegetation dynamics can contribute to grassland biomass estimations, grazing capacity predictions, and ecosystem protection (Myoung et al. 2012; Wang et al. 2013). The increasing populations of humans and livestock as well as the reclamation of grasslands for grain production and the influence of development, including mining and urbanization, have been deemed the major causes of grassland degradation on the Mongolian Plateau (Zhao et al. 2005; Addison et al. 2012; Leisher et al. 2012). Ground measurements have suggested that these human disturbances, coupled with the warmer climate, have reduced both biodiversity and ecosystem function within this region (Tong et al. 2004; Li et al. 2008; Zhang et al. 2011). However, recent publications using satellite data have recognized a more neutral situation, involving both declines and increases in vegetation activities in steppe areas (Peng et al. 2011; Sternberg et al. 2011; Li et al. 2012).

Remote sensing satellite imageries can provide consistent long-term, large-scale data for monitoring vegetation changes. Normalized difference vegetation index (NDVI) data derived from the Advanced Very High Resolution Radiometer (AVHRR) of the National Oceanic and Atmospheric Administration (NOAA) have been used to indicate vegetation changes from global to regional scales (e.g., Myneni et al. 1997; Piao et al. 2003; Xu et al. 2013). Previous studies have shown that NDVI datasets can be used as a good proxy for estimating changes in grassland vegetation cover and biomass production (Prince 1991; Verbesselt et al. 2007; Ma et al. 2010; Gao et al. 2012). Furthermore, the trends in the NDVI are clearly of great relevance to changes in climatic drivers (e.g., air temperature and precipitation), and they may also be related to non-climatic factors (e.g., rangeland management) (Nicholson 2005; Seaquist et al. 2008; Addison et al. 2012).

In contrast to phenological events in individual plants, satellite-observed phenology is related to canopy characteristics and can be used to indicate phenological patterns at the landscape scale (Reed et al. 1994; Schwartz 1998). The onset date of green-up is of high relevance to the beginning of the vegetation growth period in spring. Recent studies showed that the green-up of vegetation advanced in the temperate grasslands of China from 1982 to 2010 (Cong et al. 2013), but several other studies have not suggested a significant trend in vegetation green-up timing for either Mongolia or the Inner Mongolia Autonomous Region (IMAR) of China (Miao et al. 2013).

In this study, we use global inventory modeling and mapping studies (GIMMS) NDVI3g datasets containing a long-term time-series covering the last three decades (1982–2011), together with information on the climate and vegetation types, to provide spatially and temporally consistent analyses of the trends of vegetation cover over the Plateau. The investigation focuses on grassland, and particularly steppe vegetation, which occupies the largest rangeland area on the Plateau. Specifically, the main questions that our study addresses are as follows: (1) Did the Mongolian Plateau experience a greening trend over the period from 1982 to 2011? (2) Do the inter-annual trends in the NDVI change among different seasons, vegetation types and precipitation zones? (3) Is the trend of the NDVI in spring induced by an advance/delay in the onset data of green-up? (4) Are climatic changes and human activities the causes of the observed NDVI trends?

### Study area

The Mongolian Plateau is mainly occupied by Mongolia in the north and the IMAR of China in the south. Steppe vegetation, including meadow, typical, and desert steppe vegetation, is the most widespread vegetation type on the Plateau, occupying almost half of the entire vegetation area (Table 1). Among the three major steppe types, the highest annual mean temperature appears in desert steppe (1.2 °C in Mongolia and 5.3 °C in the IMAR), followed by typical steppe (0.0 °C vs. 3.9 °C), and meadow steppe (−1.1 °C vs. 1.9 °C), whereas the annual precipitation shows the reverse order. The climate for steppe vegetation in the IMAR is generally warmer and wetter than that in Mongolia. The average growing season NDVI varies with the vegetation type, showing the highest value in forests and the lowest value in desert. Compared with the IMAR, the average value of the NDVI for most vegetation types is lower in Mongolia, consistent with the average annual precipitation.

## Data

### NDVI products

We used the NOAA/AVHRR GIMMS NDVI3g archive (0.083° spatial resolution, bimonthly frequency, spanning 1982–2011) to explore vegetation

**Table 1** Total area, average elevation, mean annual temperature (MAT), mean annual precipitation (MAP), and growing season NDVI for six vegetation types in Mongolia and the Inner Mongolia Autonomous Region (IMAR) of China for the period from 1982 to 2011

| Vegetation type | Mongolia | | | | | IMAR, China | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Area ($10^3$ km$^2$) | Elevation (m) | MAT (°C) | MAP (mm) | NDVI | Area ($10^3$ km$^2$) | Elevation (m) | MAT (°C) | MAP (mm) | NDVI |
| TCV | 83 (5) | 2,387 ± 1,308 | −4.96 ± 2.22 | 275 ± 73 | 0.44 ± 0.12 | – | – | – | – | – |
| Forest | 195 (12) | 1,554 ± 974 | −2.54 ± 2.11 | 324 ± 60 | 0.62 ± 0.11 | 157 (13) | 706 ± 723 | 0.45 ± 3.55 | 439 ± 65 | 0.73 ± 0.14 |
| Meadow steppe | 144 (9) | 1,399 ± 710 | −1.06 ± 2.39 | 279 ± 53 | 0.52 ± 0.13 | 58 (5) | 822 ± 506 | 1.91 ± 3.02 | 363 ± 53 | 0.60 ± 0.12 |
| Typical steppe | 423 (27) | 1,444 ± 743 | 0.01 ± 2.69 | 223 ± 56 | 0.40 ± 0.13 | 279 (24) | 994 ± 482 | 3.94 ± 2.77 | 296 ± 58 | 0.42 ± 0.12 |
| Desert steppe | 84 (5) | 1,532 ± 552 | 1.17 ± 3.19 | 161 ± 51 | 0.21 ± 0.08 | 89 (8) | 1246 ± 227 | 5.27 ± 1.51 | 183 ± 37 | 0.24 ± 0.06 |
| Desert | 544 (35) | 1,316 ± 388 | 4.19 ± 2.98 | 125 ± 49 | 0.13 ± 0.10 | 282 (24) | 1280 ± 391 | 8.18 ± 1.45 | 102 ± 50 | 0.10 ± 0.06 |
| Cropland | 12 (1) | 1,191 ± 358 | −0.53 ± 1.61 | 290 ± 58 | 0.51 ± 0.10 | 107 (9) | 851 ± 880 | 5.76 ± 1.81 | 356 ± 72 | 0.46 ± 0.13 |
| Overall | 1,484 (95) | 1,472 ± 751 | 0.77 ± 3.87 | 207 ± 89 | 0.35 ± 0.21 | 972 (82) | 978 ± 609 | 4.11 ± 3.76 | 293 ± 134 | 0.45 ± 0.26 |

*Notes* TCV represents tundra and cushion vegetation. Figures in parentheses represent the percentage (%) of each vegetation type within the total land area of Mongolia and the IMAR. The values for elevation, MAT, MAP, and NDVI are shown as the mean ± standard deviation

activity on the Mongolian Plateau. This dataset is one of the most accurate products for assessing changes in vegetation growth (Tucker et al. 2005; Beck et al. 2011; Fensholt and Proud 2012), and it is widely used to depict long-term change in global and regional terrestrial vegetation cover (de Jong et al. 2013; Xu et al. 2013).

The monthly NDVI was obtained via the maximum value composite method to minimize the effects of cloud contamination, atmospheric conditions and the solar zenith angle (Holben et al. 1986). To eliminate spurious NDVI trends caused by winter snow, our analysis focused on the interannual vegetation changes during the growing season from May to September. Furthermore, we calculated the average monthly NDVI in spring (March to May), summer (June to August), and autumn (September to November) to further examine seasonal contributions. To reduce the impact of snow in early spring as well as bare soil, pixels showing seasonal temperatures of $<0$ °C and mean NDVI values of $<0.05$ were removed from the analysis (Fang et al. 2004; de Jong et al. 2012).

## Climate and vegetation type data

The monthly surface air temperature (at 1.5 meters above ground) and precipitation in the IMAR were obtained from 50 meteorological stations (National Meteorological Information Center of the China Meteorological Administration, http://www.nmic.gov.cn). We interpolated climate data to grid cells with a spatial resolution of 0.083° using a kriging interpolation algorithm (Piao et al. 2003). Temperature and precipitation data for Mongolia were derived from monthly mean temperature and precipitation data from the University of East Anglia Climatic Research Unit's Time Series 3.2 datasets for the period 1982–2011 (CRU TS3.2, http://www.cru.uea.ac.uk/cru/data/) (Harris et al. 2013). The CRU TS3.2 product is a gridded 0.5° × 0.5° product based on meteorological station data, which were converted to geographic grid cells with 0.083° × 0.083° spacing to match the NDVI dataset using the bilinear resampling method.

The spatial distribution of IMAR vegetation was obtained from a digitized Atlas of China's Vegetation, which has a scale of 1:1,000,000 (Editorial Board of

Vegetation Map of China, 2001). For Mongolia, we digitized an ecosystem map with a scale of 1:1,000,000 (Institute of Botany, Mongolia Academy of Science, 1995). Six vegetation types were identified on the Mongolian Plateau: tundra and cushion vegetation, forest, shrub, grassland, desert, and cropland (Fig. 1). Shrub vegetation was not included in this analysis because it occupies less than 1 % of the total study area.

## Methods

### Interannual trend estimation and linear correlation analysis

Ordinary least-squares analyses were applied for each vegetation pixel to estimate the linear time trends of the NDVI across the study period, and the significance level (p) of these variables was assessed using F-tests. Plateau-wide trends were derived as the average of all grid cells. The same analyses were performed at the regional scale for each vegetation type. In addition, we calculated the Pearson correlation coefficients between the detrended NDVI and climate variables (temperature and precipitation) in different seasons to investigate potential climatic drivers of the growing season NDVI trends. We assumed that the interannual variability in the NDVI was related to temporal variability in climate variables when the correlation coefficients were statistically significant.

### Distinguishing human-induced vegetation dynamics from climate change: the residual trends (RESTREND) method

The RESTREND method, based on the perception that vegetation growth in arid and semi-arid regions is mainly limited by precipitation, has been widely used to examine non-climatic effects on vegetation dynamics by removing the effects of precipitation (Evans and Geerken 2004). For each pixel, we first established linear models between the annual NDVImax (the averaged value during July and August) and the cumulative precipitation in different periods (from July to August, from May to August, and from the preceding October to August) during 1982–2011. Then, the statistically significant linear model ($p < 0.05$) with the highest $R^2$ value was chosen to generate residuals (observed vs. predicted). When no trend existed in the residuals across the study period, the changes in the NDVI were assumed to be induced by precipitation, whereas an increased or decreased trend suggested that a greening or browning trend might be attributed to human activities (Li et al. 2012).

### Extracting data on the onset of green-up

Numerous methods exist for estimating satellite-based phenological events; however, no method is accepted universally (White et al. 2009; Schwartz and Hanes 2010). Here, using the pixel NDVI threshold approach, which can be applied easily and is suitable for different vegetation types, we extracted the time of vegetation green-up in each pixel for each year. First, the Savitzky and Golay smoothing filter (Savitzky and Golay 1964) was used to execute data filtering and to reconstruct the annual NDVI time series curve. Second, the onset of green-up was defined as having occurred once the NDVI exceeded the annual mean value on three consecutive occasions. Finally, the inter-annual trends in the timing of the onset of green-up were examined by performing a linear regression of the green-up onset dates against the year from 1982 to 2011. Negative and positive values indicated advanced or delayed green-up, respectively.

All statistical analyses were conducted in MATLAB for Windows (Version 2010b, The MathWorks, Inc., USA) and ArcGIS (Version 9.3, ESRI, Inc., USA).

## Results

### Annual and seasonal NDVI changes

The interannual variations in the growing season NDVI were analyzed to reveal the trend of vegetation growth on the Mongolian Plateau over the past 30 years (Fig. 2). We did not observe a statistically significant trend in the NDVI across the entire study period. However, there was a distinct period showing a significant increase (0.001 $y^{-1}$) from 1982 to 1998 ($r^2 = 0.44$, $p < 0.01$), followed by a sharp decrease until 2007 and a subsequent increase. This pattern can be explained partly by the variation in annual precipitation ($r^2 = 0.37$, $p < 0.01$), which increased prior to 1998 and then declined rapidly after 1999. The interannual variations of the NDVI were similar in

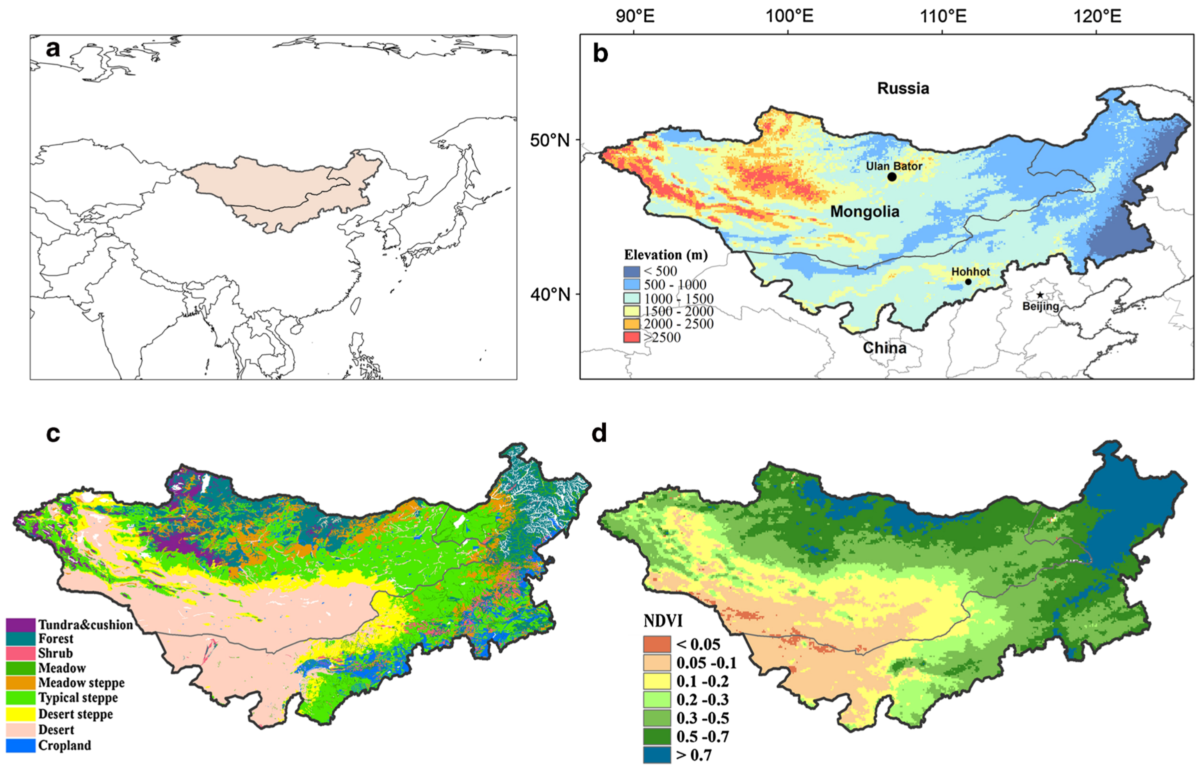


**Fig. 1** Location of the Mongolian Plateau (**a**) and maps of elevation (**b**), vegetation types (**c**), and the average monthly NDVI in the growing season (May–September) (**d**) from 1982 to 2011 across the Plateau

different precipitation zones, except for in the most humid area (mean annual precipitation > 400 mm), where a weak increase was observed ($r^2 = 0.12$, $p = 0.06$) (Fig. 3).

The spatial patterns of the seasonal NDVI trends also showed high heterogeneity (Fig. 4). In general, the NDVI in the growing season increased in 11 % of the study area, mainly in the forests and meadows of northern Mongolia and IMAR, the croplands in the south of the Horqin sandy land, and the steppes of the Ordos highland. Significantly negative NDVI trends were found across 19 % of the Plateau, mainly in northern Mongolia and east of the IMAR, which were areas dominated by steppe vegetation. In spring, the NDVI exhibited a significantly positive trend over 29 % of the study area, whereas only 8 % of the study area showed an increase in summer, which mainly occurred in the Hangai Mountains of Mongolia, south of the Horqin sandy land, and the in Ordos highland in the IMAR. In summer, a decrease in the NDVI occurred in 21 % of the area, which was twice the percentage in spring (13 %) and autumn (12 %).

## NDVI changes by vegetation type

Over the past three decades, the NDVI showed no statistically significant linear trend for any vegetation type in summer, autumn, or the growing season (Table 2; Fig. 5). However, during spring, a conspicuous increase occurred in grasslands and cultivated vegetation, both of which displayed an average annual increase of $0.5 \times 10^{-3}\ y^{-1}$ ($p < 0.05$). We also found that all three steppe types exhibited a significantly positive trend across Mongolia ($p < 0.05$). Large increases appeared in the typical steppe vegetation, with a total increase of 13 % being recorded, followed by the meadow steppe (11 %) and desert steppe (1 %). However, in the IMAR, a significantly increasing trend was found only in the meadow steppe (7 %) and typical steppe vegetation (5 %) ($p < 0.05$).

We further explored the interannual variations in the percentages of the land area showing different NDVI levels for steppe vegetation in the IMAR (Fig. 6a) and in Mongolia (Fig. 6b) during the growing season from 1982 to 2011. Despite finding no significant linear trends in the

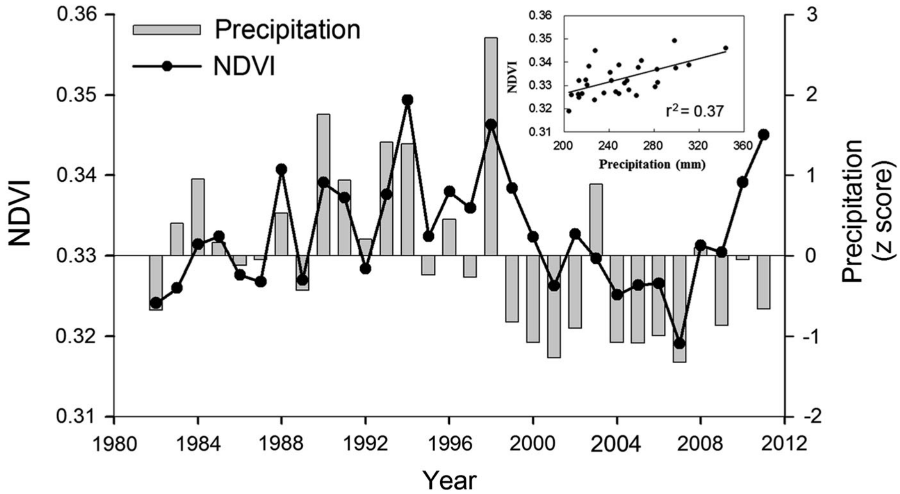


**Fig. 2** Interannual variations in the growing season NDVI and annual precipitation (expressed as Z-scores) on the Mongolian Plateau from 1982 to 2011. The inset graph denotes the relationship between the NDVI and annual precipitation

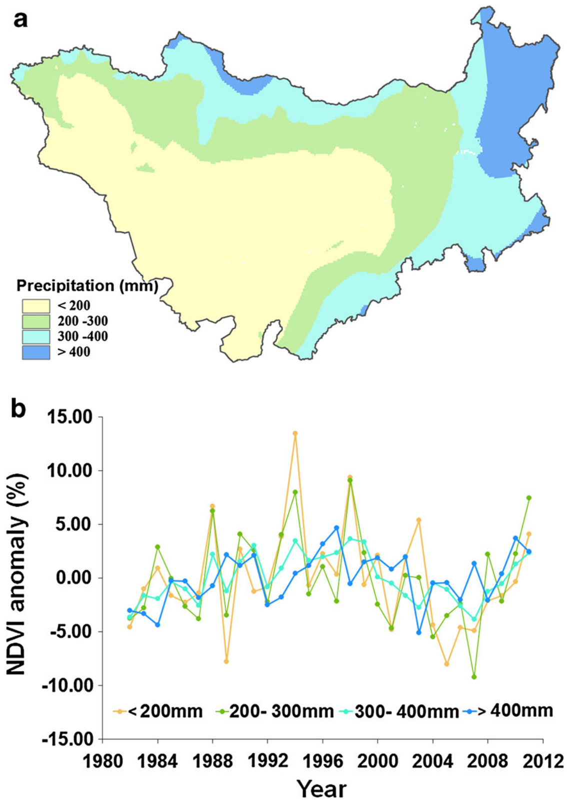


**Fig. 3** Interannual variations in the growing season NDVI in different precipitation zones (mean annual precipitation <200 mm; 200–300 mm; 300–400 mm; >400 mm) on the Mongolian Plateau from 1982–2011. **a** Distribution of precipitation zones and **b** interannual changes in the NDVI anomaly (%) in different precipitation zones

area of each NDVI level, spatial expansion of greening (referred to here as the increase in the area with an NDVI >0.5) occurred mainly in the 1980s and 1990s, reaching percentages of 48 and 41 % in 1998 for the IMAR and Mongolia, respectively. Compared with steppe vegetation in Mongolia, the average area with an NDVI <0.2 (often corresponding to desert steppe) was clearly lower in the IMAR (6 vs. 13 %), while the area with an NDVI >0.6 (often corresponding to meadow steppe) was slightly higher (15 vs. 13 %) from 1982 to 2011.

## Interannual variations in the vegetation green-up time

As a 30-year average, the estimated date of green-up onset was between late April and late May, with an early to late progression being observed from southern to northern Mongolia, although oscillation was recorded in central Inner Mongolia (Fig. 7a). The date of green-up onset advanced for forest (−1.2 days/decade, $p < 0.05$) and meadow steppe vegetation (−1.6 days/decade, $p < 0.01$), whereas no widespread advance was found for the other vegetation types in the IMAR. In Mongolia, only meadow steppe vegetation showed a weak advance in the date of green-up onset (−1.3 days/decade, $p = 0.06$). Thus, an advancing trend in green-up onset occurred mostly over the northern part of the Plateau, whereas a delaying trend appeared sporadically in highly populated southern areas, such as on the Hetao plain in the IMAR (Fig. 7b).

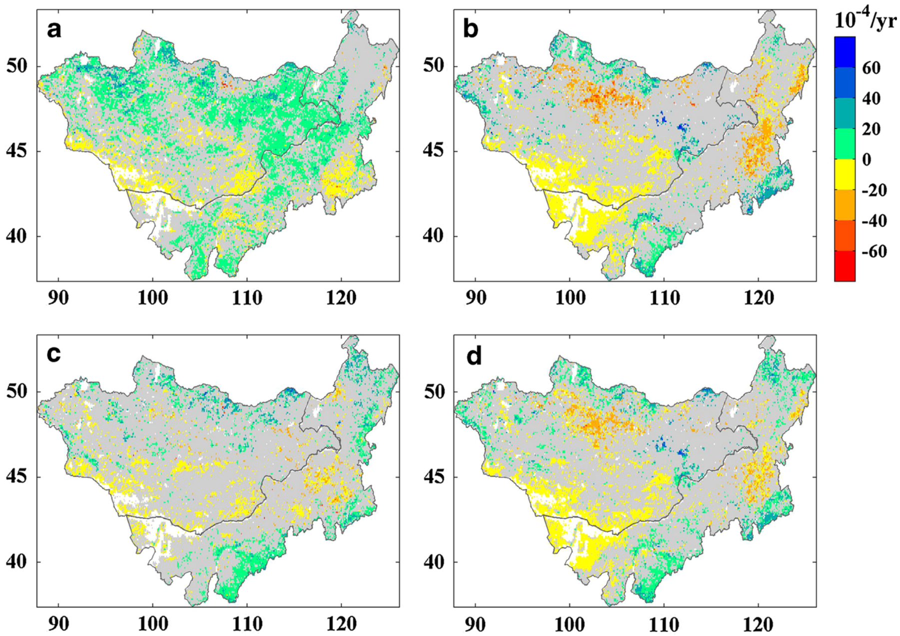


**Fig. 4** Spatial patterns of NDVI trends in different seasons on the Mongolian Plateau from 1982 to 2011: **a** spring (March–May), **b** summer (June–August), **c** autumn (September–November), and **d** the growing season. The areas where the mean seasonal NDVI was below 0.05 and the mean seasonal temperature was lower than 0 °C were excluded from the analysis to remove the bias caused by snow cover. Only pixels showing a statistically significant trend ($p < 0.05$) are *colored*, and the *gray* areas indicate no significant change ($p \geq 0.05$). (Color figure online)

**Table 2** Linear trends in the seasonal mean NDVI for major vegetation types from 1982 to 2011 on the Mongolian Plateau

| Vegetation type | Growing season | | | Spring | | | Summer | | | Autumn | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Slope | $r^2$ | *P* value | Slope | $r^2$ | *P* value | Slope | $r^2$ | *P* value | Slope | $r^2$ | *P* value |
| TCV | 3.21 | 0.04 | 0.30 | 5.50 | 0.12 | 0.06 | 5.30 | 0.04 | 0.27 | 4.55 | 0.05 | 0.26 |
| Forest | 2.50 | 0.02 | 0.42 | 5.57 | 0.06 | 0.19 | −1.20 | 0.00 | 0.74 | 6.87 | 0.10 | 0.09 |
| Grassland | −0.34 | 0.00 | 0.92 | **5.41** | **0.31** | **0.00** | −1.60 | 0.00 | 0.71 | 0.92 | 0.00 | 0.72 |
| Desert | −1.89 | 0.08 | 0.13 | 0.17 | 0.00 | 0.81 | −2.44 | 0.12 | 0.06 | −1.31 | 0.04 | 0.31 |
| Cropland | 1.08 | 0.00 | 0.75 | **4.81** | **0.23** | **0.01** | −0.51 | 0.00 | 0.91 | 5.29 | 0.11 | 0.07 |

*Notes* TCV represents tundra and cushion vegetation, and the unit of the slope is $10^{-4}$

Bold numbers indicate statistically significant trends ($p < 0.05$)

## Climatic drivers of NDVI change

The annual temperature showed a remarkable increase in both Mongolia and the IMAR, with a rate of 0.04 °C $y^{-1}$ ($p < 0.01$) (Table 3). The monthly mean temperature for all seasons other than winter increased significantly, with the largest magnitude occurring in summer. However, for seasonal precipitation a significant decrease appeared in summer, showing a rate of 1.40 mm $y^{-1}$ ($p < 0.05$) in Mongolia and 2.13 mm $y^{-1}$ in the IMAR ($p < 0.01$). The annual precipitation decreased over the Mongolian Plateau, despite the marginal increase recorded in spring for Mongolia and in winter for the IMAR. Overall, continuous warming and fluctuations in precipitation have clearly occurred on the Mongolian Plateau over the last three decades.

No significant correlation between the growing season NDVI and temperature was found in Mongolia, whereas precipitation accounted for nearly half of the variance in the NDVI ($p < 0.01$). A similar NDVI-climate relationship was observed in the IMAR, but

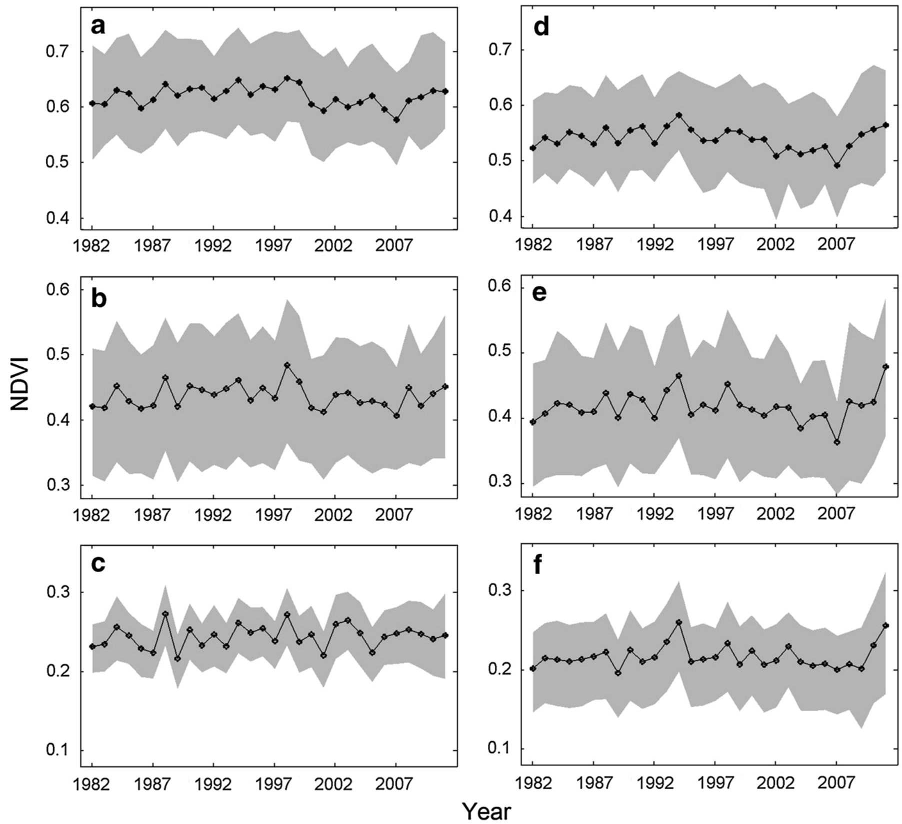


**Fig. 5** Interannual variability in the growing season NDVI for meadow steppe (**a** IMAR, **d** Mongolia), typical steppe (**b** IMAR, **e** Mongolia) and desert steppe vegetation (**c** IMAR, **f** Mongolia) from 1982 to 2011. The *gray* area represents the range of the NDVI between the 25 and 75 % quantiles. (Color figure online)

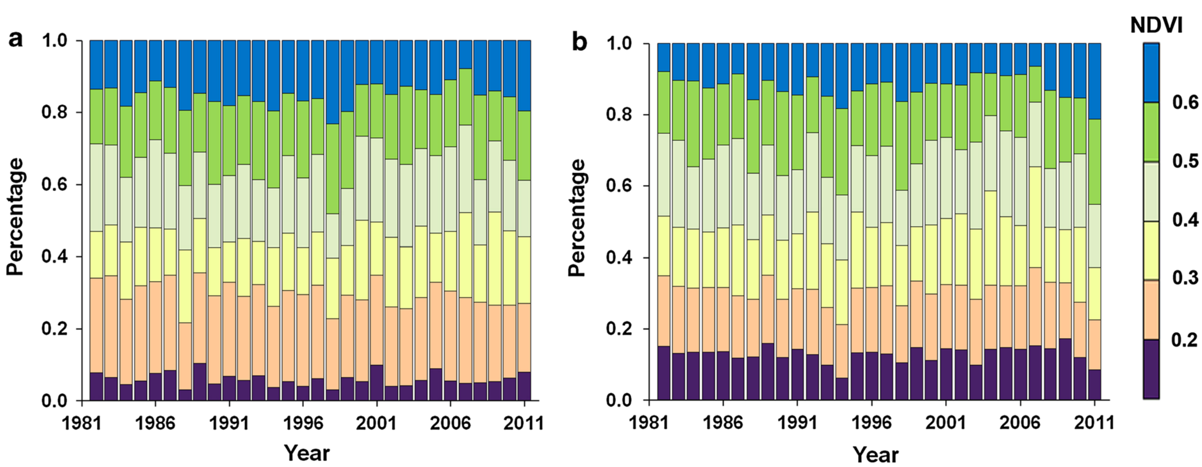


**Fig. 6** Interannual variations in the percentages of land areas showing different growing season NDVI levels for steppe vegetation from 1982 to 2011. The steppe vegetation includes meadow steppe, typical steppe and desert steppe vegetation. **a** IMAR of China; and **b** Mongolia

precipitation only accounted for 30 % of the variation in the NDVI, indicating the existence of non-climatic effects on NDVI dynamics in this area. Seasonal precipitation, particularly in summer, showed significant impacts on the variation in the growing season NDVI for steppe vegetation in both Mongolia and the IMAR (Table 4). Although the temperature in all seasons displayed no significant correlation with the growing season NDVI, a significant positive relationship was observed between the NDVI and temperature

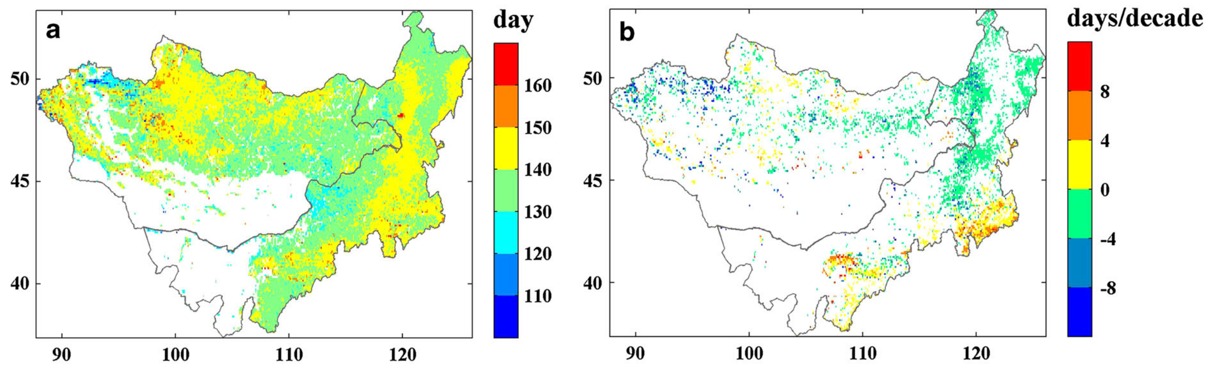


**Fig. 7** Average green-up onset date (**a**) and its rate of change (**b**) on the Mongolian Plateau from 1982 to 2011. The *white color* denotes sparse vegetation cover or pixels without a statistically significant trend ($p < 0.05$). (Color figure online)

in spring for meadow steppe vegetation in Mongolia ($r = 0.49$, $p < 0.05$) and in the IMAR ($r = 0.\ 56$, $p < 0.01$). Furthermore, the warming temperature in spring advanced the onset of green-up for meadow steppe vegetation in the IMAR ($r = 0.38$, $p < 0.05$). These results implied that the major drivers of seasonal NDVI dynamics differ by season and vegetation type.

Non-climatic influence on changes in the NDVI

The RESTREND method was used to distinguish vegetation changes caused by human activities from those caused by climatic changes. The interannual trends of the residuals from the NDVImax–precipitation regressions exhibited similar spatial patterns to trends in the growing season NDVI. The areas showing positive NDVI trends in the southern Horqin sandy land and western Mu Us sandy land (Fig. 4d) also displayed positive residual trends (Fig. 8). A negative residual trend was pronounced over the northern and central areas of the Mongolian Plateau, encompassing areas mainly occupied by forest and meadow steppe vegetation. In southern Mongolia and the western IMAR, certain pixels of desert steppe vegetation also showed a decreasing trend in the residuals.

## Discussion

Spatiotemporal patterns of vegetation change

The average satellite-retrieved change in the NDVI demonstrated that there was no linear trend in the growing season NDVI across the Mongolian Plateau from 1982 to 2011, whereas an overall greening appeared during 1982–1998. This is in agreement with the results of previous studies showing that piecewise regression models work well in the eastern IMAR and that no significant change, or even a declining trend, occurred after the 1990s (Ma et al. 2010; Peng et al. 2011). A similar reverse trend was evident on the Mongolian steppe, with a 16 % decline in vegetation cover being reported (Park and Sohn 2010; Sternberg et al. 2011).

Regarding the spatial pattern of the change in the NDVI, the growing season NDVI increased in only 11 % of the study area, mainly in the southern Horqin sandy land and the Ordos highland. Possible drivers of this increase include active measures to halt desertification, such as grassland restoration and conservation, rather than changes in precipitation (Xu et al. 2010; Li et al. 2012). The bulk of pixels displaying a negative trend was found in the central eastern IMAR, mainly corresponding to typical and meadow steppe vegetation, where vegetation growth was constrained by a blend of precipitation and human activities. For example, Tong et al. (2004) and Kawada et al. (2011) reported that farming may lead to desertification on the Xilingol steppe and that the degraded areas of the steppe increased dramatically from 1985 to 1999. Although a widespread, but marginal, decreasing trend is discernible in the Gobi desert, it should be verified with a ground-based investigation due to the insufficient precision of the NDVI value obtained for such limited vegetation cover (often presenting an annual NDVI between 0.05 and 0.1) (Pettorelli et al. 2005; Sternberg et al. 2011). In addition, linear trends are not always meaningful in this highly dynamic

**Table 3** Mean changes in annual and seasonal temperature and precipitation in Mongolia and Inner Mongolia from 1982 to 2011

| Region | Temperature (°C) | | | | | Precipitation (mm) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Spring | Summer | Autumn | Winter | Annual | Spring | Summer | Autumn | Winter | Annual |
| Mongolia | 0.05* | 0.09** | 0.04 | 0.00 | 0.04** | 0.40* | −1.40* | −0.32* | 0.05 | −1.26* |
| Inner Mongolia | 0.04* | 0.07** | 0.04* | 0.02 | 0.04** | 0.32 | −2.13** | −0.14 | 0.09* | −1.87* |

*Notes* Double and single asterisks denote statistical significance at the 1 and 5 % levels, respectively

**Table 4** Correlation coefficients between the growing season NDVI and temperature ($R_{NDVI\text{-}T}$) or precipitation ($R_{NDVI\text{-}P}$) in different seasons (the preceding winter, spring, summer, and autumn) for the three main steppe types and all vegetated areas in Mongolia and the Inner Mongolia Autonomous Region (IMAR) from 1982 to 2011

| Region | Grassland type | NDVI-Temperature ($R_{NDVI\text{-}T}$) | | | | NDVI-Precipitation ($R_{NDVI\text{-}P}$) | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Win | Spr | Sum | Aut | Win | Spr | Sum | Aut |
| Mongolia | Meadow steppe | −0.13 | −0.35 | −0.31 | 0.07 | −0.13 | −0.16 | 0.62** | 0.38* |
| | Typical steppe | −0.14 | −0.18 | −0.23 | 0.05 | 0.11 | 0.09 | 0.57** | 0.33 |
| | Desert steppe | −0.08 | −0.20 | −0.15 | 0.01 | 0.07 | 0.21 | 0.55** | 0.01 |
| | VA | −0.07 | −0.24 | −0.17 | 0.04 | 0.01 | 0.04 | 0.63** | 0.23 |
| IMAR | Meadow steppe | 0.18 | −0.07 | −0.25 | −0.05 | −0.04 | 0.18 | 0.53** | 0.37* |
| | Typical steppe | 0.25 | 0.03 | −0.23 | 0.12 | −0.19 | 0.28 | 0.61** | 0.01 |
| | Desert steppe | 0.15 | 0.05 | −0.14 | 0.13 | 0.00 | 0.42* | 0.66** | −0.18 |
| | VA | 0.24 | 0.01 | 0.08 | 0.06 | 0.00 | 0.34 | 0.47** | 0.08 |

*Notes* VA represents all vegetated areas. Double and single *asterisks* denote statistical significance at the 1 and 5 % levels, respectively

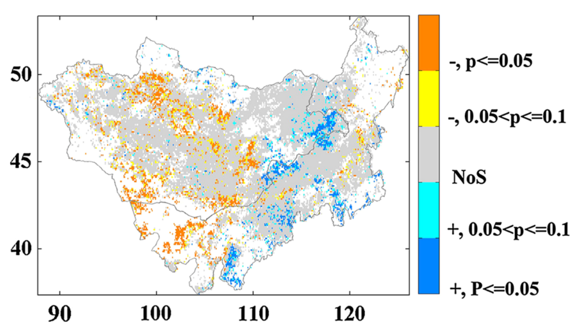


**Fig. 8** Map of the statistical significance of the residual time regression. The residuals were calculated as the difference between the observed and predicted NDVI using a linear model of NDVImax (the averaged value during July and August) and precipitation (the accumulated value from three different periods: July to August, May to August, and the preceding October to August). Only pixels showing a statistically significant trend ($p < 0.05$) are *colored*, and the *gray* areas indicate no significant change ($p \geq 0.05$). *White coloration* denotes sparse vegetation cover or pixels without a statistically significant correlation between NDVImax and precipitation ($p \geq 0.05$). (Color figure online)

environment, where considerable annual fluctuations are the normal behavior, and change is not always linear.

The positive NDVI trend observed in spring appeared to be consistent across the three main steppe types (meadow, typical, and desert steppe), implying that the existence of an advanced green-up onset or increased vegetation activity, despite the different drivers involved. The satellite-derived phenological trends confirmed that the onset of green-up advanced in the meadow steppe vegetation. This result is similar to those of Yu et al. (2003) and Cong et al. (2013), who detected an earlier onset of green-up on the north Mongolian Plateau. However, no trend of the onset date was discerned in our study for the typical and desert steppe vegetation types. It is noteworthy that the changing trends in the green-up onset date may differ among studies because of the different methods used to retrieve phenological timing (Reed et al. 1994; White et al. 2009; Cong et al. 2013). Other factors, such as differences in the sources of remote-sensing data and study periods, may lead to reversal of the detected trends (Yu et al. 2010; Piao et al. 2011; Zhang et al. 2013). In addition, the seasonal NDVI curves are likely specific for different vegetation types, and the use of only one method may result in limitations when examining the date of the onset of vegetation green-up.

### Controls of NDVI trends

The vegetation dynamics in most arid and semi-arid areas are highly sensitive to changes in precipitation (Nicholson 2005; Seaquist et al. 2008; Zhao et al. 2011; Fensholt et al. 2012). This study showed that precipitation is a primary determinant controlling the variation of the NDVI for each vegetation type. Further investigation revealed that the trend of the growing season NDVI was positively correlated with precipitation during summer, indicating that the effect corresponds to the timing and magnitude of climate variability (Fang et al. 2005; Craine et al. 2011) (Table 4). Although our results show that temperature exerts a minor or even negative effect on the plant growth of steppe vegetation, we also noted that warming was the most significant contributor to the advanced onset of vegetation green-up and increased vegetation growth in spring for the meadow steppe vegetation type. These climate-driven patterns confirm that increased temperature in relatively wetter ecosystems could enhance vegetation growth, whereas warming in water-limited ecosystems in semi-arid regions, such as typical and desert steppes, may not have any positive effect on vegetation growth (Liancourt et al. 2012).

However, precipitation, which was identified as the primary constraint on plant growth in the study area, explained only approximately 30 % of the variance in the annual NDVI in the IMAR. We detected increasing NDVI trends in some areas, such as the Mu Us sandy land, where precipitation did not show significant changes during the study period (Fig. 4). Furthermore, a positive trend in the residuals was observed in these areas (Fig. 8). Possible explanations for these findings could be associated with the active management measures implemented by the government to halt desertification (Runnstrom 2003; Xu et al. 2010). Many studies have found that enhanced anthropogenic activities in this area, such as afforestation and land abandonment, may play an important role in vegetation recovery (Li et al. 2008; John et al. 2009; Li et al. 2012). In addition, we detected negative residual trends in several areas where the NDVI decreased despite an absence of significant changes in precipitation. Overgrazing, land management, and mineral extraction may cause rangeland degradation on the plateau (Sankey et al. 2009; Addison et al. 2012). It should also be noted that RESTREND analysis may underestimate human impacts, particularly when severe disturbance or land use change has occurred (Wessels et al. 2012). RESTREND analysis is based on the assumption of significant temporal correlation between NDVImax and precipitation, but this relationship is lost when severe degradation occurs.

## Conclusions

The analysis of a 30-year time series of satellite data in this study provided a meaningful assessment of the spatial and temporal changes in the NDVI on the Mongolian Plateau. The results indicated that there was no significant increase in the growing season NDVI across the Plateau. However, local trends revealed considerable variations in the direction and magnitude of the changes that have occurred. Vegetation greening was detected for steppe vegetation in spring, which was partially consistent with the advanced onset of green-up. Precipitation was the primary climatic constraint on plant growth in the growing season, whereas temperature was positively correlated with vegetation activity in meadow steppe only in spring. Regional-scale greening/browning patterns, likely due to regional policy and human impacts, should be further examined using ground-based investigations.

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