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RESEARCH ARTICLE

Long-term vegetation changes in the four mega-sandy lands in Inner Mongolia, China

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Abstract

Context Desertification in China has become one of the most serious ecological and social problems. The four mega-sandy lands (Hulunbeir, Horqin, Otindag, and Mu Us) in Inner Mongolia are reported to be the most widespread and seriously desertified areas in China.

Objectives To explore changes of vegetation activity and the possible driving forces in the four mega-sandy lands over the last three decades.

Methods We investigated spatiotemporal variations in the growing-season (May–September) normalized difference vegetation index (NDVI) and their relationships with climate factors and human activities during 1982–2011, using two NDVI datasets from Global Inventory Modelling and Mapping Studies (GIMMS) and Moderate Resolution Imaging Spectroradiometer (MODIS).

Results We found a significant overall NDVI increase in Mu Us, but no such trends in the other three. A significant increase was in south and northeast Mu Us and southeast Horqin, and a decrease in south Hulunbeir, northwest Horqin, and central Otindag. NDVI trends were positively correlated with precipitation and uncorrelated with temperature and wind speed in all sandy lands except Mu Us.

Conclusions NDVI trends showed a large spatial heterogeneity in the four sandy lands. Precipitation was a major determiner for the interannual variations and spatial patterns of NDVI at regional scale, whereas human activities were the cause of NDVI variations at local scale. The consistent interannual variations between two NDVI datasets of GIMMS and MODIS for all four sandy lands suggested that GIMMS NDVI was appropriate for investigating long-term vegetation changes in sandy lands.

Keywords Climate change · Human activity · Desertification · Sandy land · Vegetation change · NDVI

Introduction

Desertification in arid, semiarid and dry sub-humid regions is a major global environmental issue

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(UNCCD 2004; Adeel et al. 2005). Around 4–8 % of earth's land surface has been undergoing desertification, directly affecting some 250 million people in developing countries (Reynolds et al. 2007; Vogt et al. 2011). Desertification in China has influenced more than a quarter of national land area and become one of the most serious ecological and social problems (Fullen and Mitchell 1994; Liu and Diamond 2005; State Forestry Administration 2011; Wang et al. 2013). The four mega-sandy lands, i.e., Hulunbeir, Horqin, Otindag and Mu Us, are the most typical areas undergoing extensive desertification in the country (Zha and Gao 1997; Zheng et al. 2006). These sandy areas, mainly located in eastern Inner Mongolia and the Ordos Plateau, are within the agro-pastoral transitional zone of northern China, where ecosystems are typically sensitive and fragile to climate change and human activities (Zhu et al. 1980; Wang et al. 2002; Han et al. 2010; Zhang et al. 2012). Thus, investigating the process of desertification and its driving factors could help to promote the management strategies of desertification control in these sandy lands.

The aggravation of desertification was detected in the four mega-sandy lands before the 1990s in many previous studies (Yang et al. 2007; Bagan et al. 2010). For example, Wu and Ci (2002) recognized that the area of shifting sandy dunes in Mu Us increased by 5,400 km^2 between the 1950s and 1990s and covered 44.5 % of the total area in the 1990s; Liu and Wang (2007) found that sandy area with high degradation increased by 1,232 km^2 during 1977–1987 in Zhenglan Banner in central Otindag; and Wu (2004) detected a rapid expansion of sandy area by 9,624 km^2 over 1975–1987 in Horqin. Most previous studies recognized the anthropogenic factors (i.e., increasing population, unsuitable reclamation and overgrazing) as the main driving forces of the rapid desertification before the 1990s (Liu and Diamond 2005; Liu and Wang 2007; Wang et al. 2013), while natural effects, such as climate warming, as a minor driver (Wang et al. 2002).

However, recent studies have suggested that desertification has slowed down and even reversed in some areas in the four sandy lands since 2000, due to the implementation of ecological restoration projects (Ao et al. 2010; Han et al. 2010; Stokes et al. 2010). Vegetation monitoring studies also found the increase of vegetation activity in 81.9 % area of Mu Us (Yan et al. 2012) and 76 % area of Horqin (Zhang et al. 2012) in the 2000s, based on Enhanced Vegetation Index from Moderate Resolution Imaging Spectroradiometer (MODIS) and normalized difference vegetation index (NDVI) from SPOT-VEGETATION, respectively.

These studies are mainly based on remote sensing images only in a few years, and may have difficulties in revealing long-term desertification process and vegetation changes in sandy lands (Li et al. 2011). Thus, a comprehensive analysis of long-term vegetation changes is necessary for evaluating desertification process in the four sandy lands. Based on the long time series (1982–2011) of GIMMS NDVI data, this work therefore aimed to investigate the vegetation changes and its potential climatic drivers in the four mega-sandy lands over the past three decades. We further evaluated the non-climatic causes of vegetation changes at each sandy lands to detect potentially human-induced land degradation as well as rehabilitation at regional scale.

Study area, data and methods

Study area

According to the desert map of China (Zhu et al. 1980), sandy land maps in related literature and the sand-covered desert classification map of China at scale 1:100,000 (http://westdc.westgis.ac.cn), we bounded the four mega-sandy lands (i.e., Hulunbeir, Horqin, Otindag and Mu Us) (Fig. 1). Hulunbeir consists of three sandy zones from north to south between Hailar city and Hulun Lake, and has the smallest area (7.5×10^3 km^2) among the four mega-sandy lands. Horqin is in the transition zone between the Inner Mongolian Plateau and the Northeast Plain, and has the largest area (73.3×10^3 km^2). Otindag is in the southern part of Xilingol Grassland in eastern Inner Mongolia, and Mu Us is in the transitional region between the Ordos Plateau and Loess Plateau. Eolian sand is the major soil type in the four sandy lands (Zheng et al. 2006). The main sand land types include fixed and semi-fixed sand dunes in all sandy lands except Mu Us, where shifting sand dunes covered most of the region (Wu and Ci 2002; Zhang et al. 2011). The dominant vegetation type in the four mega-sandy lands is typical steppe, covering more than half the study areas, and forest, shrub, farmland and other types of vegetation are scattered in the remaining areas

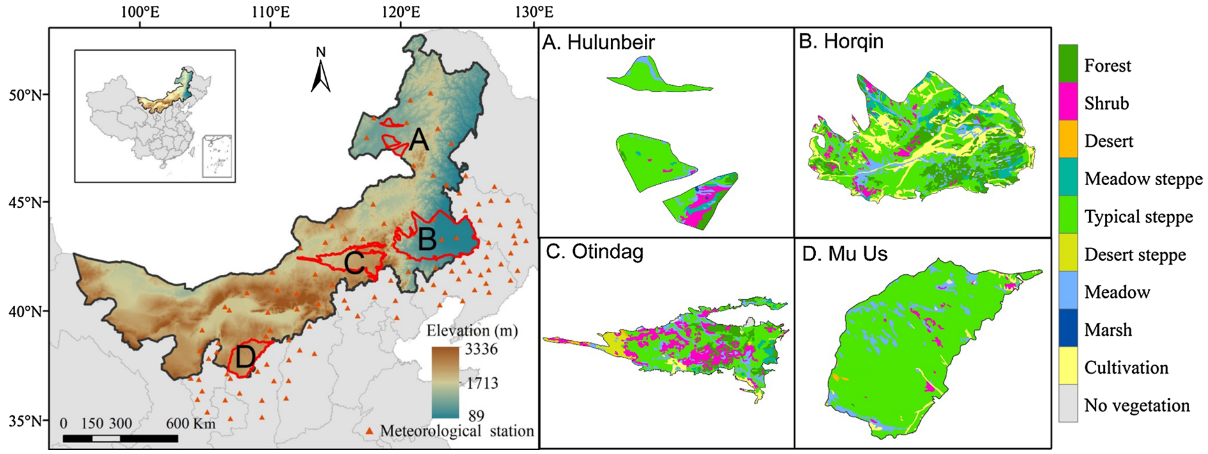

Fig. 1 Location (*left*) and vegetation distribution (*right*) of the four mega-sandy lands in China

(Fig. 1; Table 1). In this work, areas of the sandy lands outside the Inner Mongolia Autonomous Region, such as small parts of the Mu Us in Shaanxi and Ningxia, were excluded from analysis.

The four mega-sandy lands are under the typical continental monsoon climate, which changes from semi-humid in the east to semiarid in the west. Horqin has the optimal climate, with mean annual temperature (MAT) of 5–7.5 °C and mean annual precipitation (MAP) of 400–700 mm. Hulunbeir, at high latitude, has lower temperature and less precipitation (MAT $= -1.5$ to 1 °C, MAP $=$ 250–500 mm). MAT in Otindag is about 4–6.4 °C, and MAP about 250–400 mm. Mu Us has the highest temperature (MAT $=$ 7–9.5 °C) but less precipitation (MAP $=$ 250–400 mm). Annual wind speed in these sandy lands averages between 2 and 3 m/s (Table 1), but is stronger in spring with speeds as high as 5 m/s. And the strong wind in spring is recognized as the main trigger of sandstorms in North China.

By comparing spatial patterns of vegetation distribution among the four sandy lands, we found higher landscape shape index (LSI) and Shannon's evenness index (SHEI) in Horqin and Otindag, suggesting that the fragmentation of vegetation landscape was greater in these two sandy lands. Forest and farmland were widely occurred in central and southeastern Horqin, and the grass-shrub ecotone occupied most areas in central Otindag (Fig. 1). The vegetation landscape was simpler in Hulunbeir and Mu Us, where more than two-thirds of the area was covered by typical steppe. However, vegetation cover in these two sandy lands varied substantially. Hulunbeir was mainly covered by grasses and desertification was much less, whereas Mu Us was the most severely desertified, with 36 % of its area covered by shifting sand dunes. Details on the landscape indices, see Appendix A.

NDVI dataset

We used the NDVI3g dataset at 15-day interval and 0.083° spatial resolution for the period 1982–2011. This NDVI dataset was produced by GIMMS group from the advanced very high resolution radiometers onboard the National Oceanic and Atmospheric Administration's satellites (Tucker et al. 2005). The GIMMS NDVI3g datasets have removed the effects of solar zenith angle, stratospheric aerosols, sensor errors and volcanic eruptions (Fensholt and Proud 2012). To reduce atmospheric effects, scan angle effects and cloud contamination, we derived monthly NDVI from images in each month using the maximum value composite (MVC) method (Holben 1986). Pixels with annual mean NDVI less than 0.1 over 30 years were considered as non-vegetated areas, and excluded from the analysis. To avoid spurious NDVI trends from winter snow, we used the growing-season (May–September) NDVI to analyze interannual variations of vegetation activity in sandy lands.

The MODIS 250 m, 16-day NDVI product (MOD13Q1) from 2000 to 2011 was obtained from the EOS data gateway (ftp://e4ftl01.cr.usgs.gov/). This product was built from a 16-day compositing period using the Constrained View Angle Maximum

Table 1 General information on geography, climate and vegetation for the four mega-sandy lands

Sandy land	Location			Area	Climate			NDVI	Area ratio of main vegetation types (%)				Landscape index	
	Lon (°)	Lat (°)	Alt (m) Mean ± SD	(10^3 km^2)	T (°C) Mean ± SD	P (mm) Mean ± SD	W (m/s) Mean ± SD	Mean ± SD	Forest	Shrub	Grass-land*	Farm-land	LSI	SHEI
Hulunbeir	117.9–119.7	47.7–49.5	682 ± 73	7.5	0.01 ± 0.73	383 ± 86.42	2.72 ± 0.15	0.53 ± 0.03	6.6	9.9	82.9	0.2	2.41	0.54
Horqin	118.1–123.7	42.7–45.0	349 ± 211	73.3	6.40 ± 0.62	517 ± 89.02	2.74 ± 0.18	0.48 ± 0.02	19.7	4.0	57.8	18.2	15.70	0.77
Otindag	111.8–117.6	41.9–43.7	1,220 ± 124	31.6	5.40 ± 0.67	332 ± 51.90	2.88 ± 0.16	0.40 ± 0.02	12.5	22.7	59.6	3.3	8.14	0.80
Mu Us	107.4–110.2	37.6–39.4	1,343 ± 55	23.7	8.51 ± 0.71	340 ± 51.55	2.31 ± 0.13	0.27 ± 0.02	0.03	1.7	95.8	2.0	4.62	0.24

Geographic variables are location [*Lon* longitude, *Lat* latitude, *Alt* altitude] and area of the four sandy lands. Climatic variables include mean annual temperature (T), mean annual precipitation (P) and mean annual wind speed (W) of sandy lands during 1982–2011. Vegetation variables include annual growing-season (May–September) NDVI during 1982–2011, area ratio of the main vegetation type, and landscape indices in the four sandy lands. The landscape indices include landscape shape index (LSI) and Shannon's evenness index (SHEI)

* Grassland includes typical steppe, meadow steppe, desert steppe and meadow

Value Composite (CV-AMVC) algorithm, and removed effects of atmospheric gases, thin cirrus clouds and aerosols (Huete et al. 2002). To ensure consistency of the two NDVI datasets, we adopted the same data processing as the GIMMS NDVI3g.

Meteorological data and vegetation map

Monthly meteorological data were acquired from China Meteorological Data Sharing Service System (http://cdc.cma.gov.cn/), including monthly mean air temperature, monthly precipitation and monthly mean wind velocity from 1982 to 2011. Meteorological data of each sandy land was calculated from meteorological stations within or in the vicinity of each sandy land.

The vegetation distribution in the four mega-sandy lands was obtained from the digitized vegetation map of China at scale 1:1,000,000 (Editorial Board of Vegetation Map of China 2001). We classified the vegetation into nine types: forest, shrub, desert, meadow steppe, typical steppe, desert steppe, meadow, marsh and cultivation. Figure 1 shows the spatial distribution of the nine vegetation types in all four sandy lands. Vegetation maps at spatial resolution 0.083° were generated to correspond to GIMMS NDVI.

NDVI analysis method

To investigate interannual variations of vegetation activity in sandy lands, we applied the linear regression to the NDVI time-series using ordinary least-squares method, and tested the significance level (p) by *F* tests. We then calculated the Pearson correlation coefficients between the detrended NDVI and climate variables (temperature, precipitation and wind speed) to explore the impact of climatic factors on NDVI trends over the past three decades in the four sandy lands.

Some recent studies found that GIMMS NDVI in the 2000s showed different variations with NDVIs from other sensors in the alpine steppe in the Tibetan Plateau (Zhang et al. 2013). The more recent NDVI dataset from Terra MODIS is considered an improvement over GIMMS NDVI, with much higher spatial and spectral resolutions (Huete et al. 2002). Thus, we compared the interannual variations of growing season NDVI from GIMMS and MODIS over 2000–2011 to verify the reliability of GIMMS NDVI to investigate vegetation changes in the four mega-sandy lands.

RESTREND method

Residual trend (RESTREND) analysis was used to detect the impact of human activities on vegetation changes in the study area (Archer 2004; Herrmann et al. 2005; Wessels et al. 2007, 2012). We first conducted linear regressions between $NDVI_{max}$ (the annual maximum NDVI value) and accumulated precipitation during 1982–2011. To explore the best-fit statistical relationship, $NDVI_{max}$ was regressed against three precipitation variables: annual precipitation, and accumulated precipitation in the growing season (May–September) and summer (June–August). The regression equation with the highest R^2 was selected for RESTREND analysis. The significance level (p) was tested by *F* tests and only those with significant regression models ($p < 0.1$) were kept in the analysis. The trends of residuals were then analyzed for detecting the impact of human activities. If residuals showed significant trends, the vegetation changes were considered attributable to human activities which had continuing impact in one direction (in a bad way or good way); otherwise, no significant trends indicated that vegetation changes were induced by more complicated causes.

Results

Spatial patterns of NDVI

Spatial patterns of average growing-season NDVI were consistent with climate conditions of the sandy lands. Hulunbeir and Horqin, with moist conditions, had much higher NDVI than the other two sandy lands (Fig. 2). Hulunbeir has the highest regional average NDVI (0.53) and 47 % of the sandy land had values higher than 0.55, mainly in forest and shrub in the southern part. NDVI in southwest Horqin ranged from 0.35 to 0.45, covering 24 % of sandy areas, whereas NDVI in northeast Horqin was higher (0.45–0.55), covering 59 % of sandy areas, in which forest and farmland were widespread. NDVI in Otindag increased from 0.22 in the west desert steppe to 0.57 in the East Meadow. Mu Us had the lowest regional average NDVI (0.27) among the four sandy lands, owing to the warm and dry conditions.

Interannual variation of NDVI

Interannual variations of growing-season NDVI in the four mega-sandy lands during 1982–2011 are shown in Fig. 3. Mu Us was the only sandy land with significantly increasing NDVI, while no trends were found in the other three. NDVI in Mu Us rapidly increased in the 1980s (1982–1988) and late 2000s (2005–2011). Although no trends were found over the entire 30 years in Horqin and Otindag, NDVIs increased significantly from 1982 to 1999, at rates 2.2×10^{-3} year^{-1} ($p < 0.001$) and 1.3×10^{-3} year^{-1} ($p = 0.043$), respectively.

Decadal-averaged NDVI (Fig. 4) showed trends similar to annual NDVI. Among the four sandy lands, only Mu Us had a persistent increase in this variable. The other three had maximum NDVIs in the 1990s.

Variation of seasonal NDVI in grasslands

Decadal-averaged seasonal NDVIs in grasslands were highest in summer and lowest in spring in all four sandy lands. No obvious difference was observed in spring grassland NDVI among different periods. Grassland NDVI in summer and autumn had maximum values in the 1990s for Hulunbeir, Horqin and Otindag, except for summer NDVI in Hulunbeir. Summer and autumn grassland NDVI in Mu Us persistently increased from 0.268 and 0.17 in the 1980s to 0.288 and 0.188 in the 2000s, respectively (Table 2).

Spatial patterns of NDVI trends

The growing-season NDVI trends showed a large spatial heterogeneity in the four mega-sandy lands (Fig. 5). There were no obvious NDVI trends in most areas of Hulunbeir and Otindag, except for some shrub areas in south Hulunbeir and the grass-shrub ecotone in central Otindag, where NDVI decreased significantly. Significantly decreasing trends of NDVI were in northwest Horqin, and meaningfully increasing NDVI trends in southeast Horqin. The areas with increased NDVI in Horqin were mainly occurred in the region of farmlands and woodlands, where NDVI values was higher. NDVI had increased in 69 % of Mu Us over the past 30 years, and uptrends in the southern portion were greater.

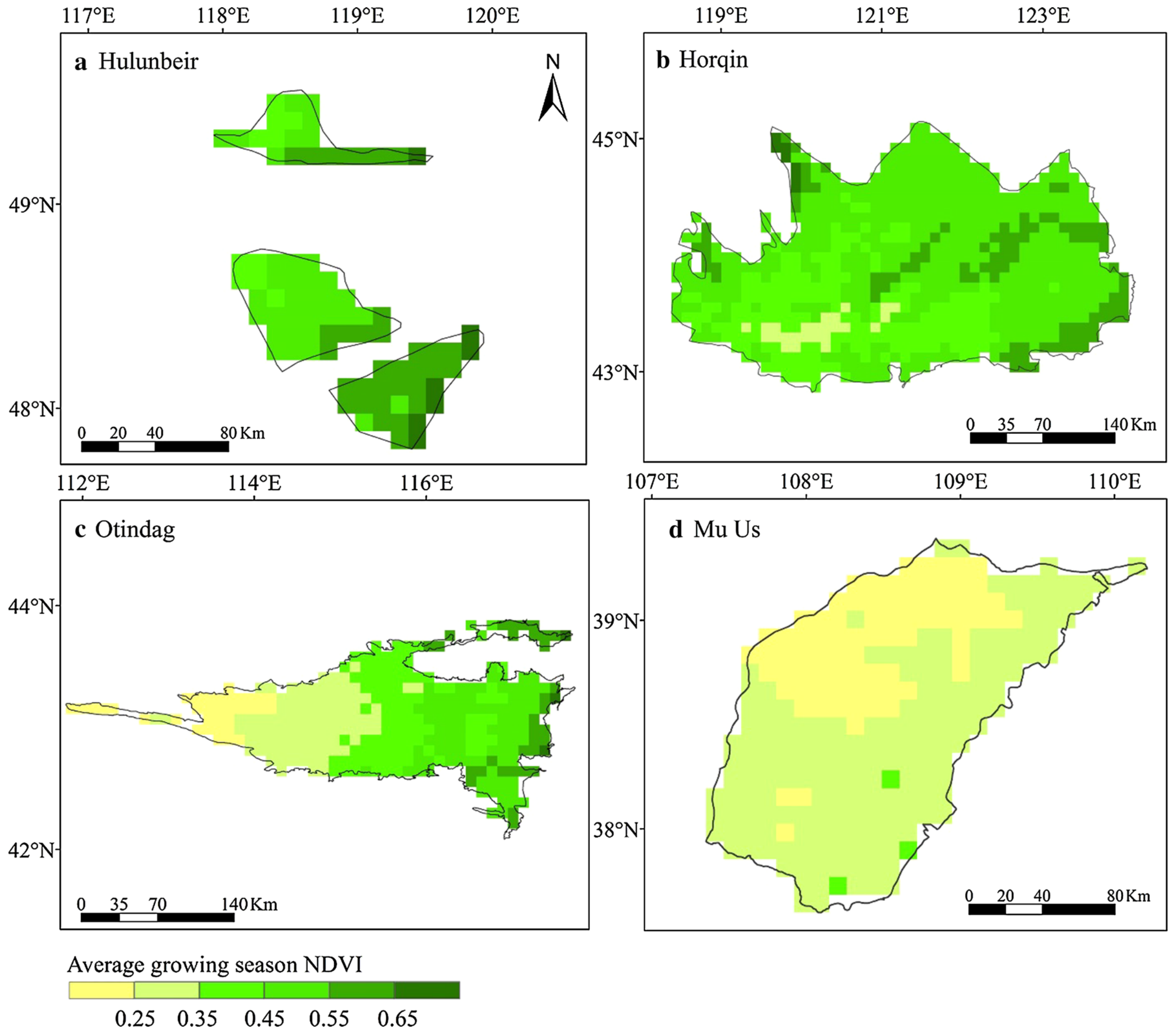

Fig. 2 Spatial pattern of average growing season (May–September) NDVI from 1982 to 2011 in the four mega-sandy lands

Possible driving factors of NDVI changes

Table 3 summarizes trends of climatic factors and their correlation coefficients with NDVI in the four mega-sandy lands. Consistent warming was observed in all four during 1982–2011, with the greatest magnitude of 0.053 °C/year in Mu Us. There was no trend in precipitation in all sandy lands except Hulunbeir, where it was −4.182 mm/year. Wind speeds decreased significantly in all four during the past 30 years, with the biggest drop of −0.018 m/s year in Otindag.

No significant correlations were found between temperature and NDVI, or between wind speed and NDVI, whereas precipitation was positively correlated with NDVI in all sandy lands except Mu Us (Table 3). Moreover, the growing-season NDVI anomalies and annual precipitation anomalies kept consistent fluctuations in all sandy lands except Mu Us (Fig. 6). Precipitation and NDVI in Hulunbeir were all above the average before 1998, but from then both were almost below the average (Fig. 6a). There were sharp decreases of precipitation in Horqin and Otindag at the end of the 1980s and during 1998–2002, meanwhile, NDVI decreased significantly to its lowest value in the same periods (Fig. 6b, c). However, Mu Us showed some exceptions, with no significant trend of precipitation but obvious uptrends of NDVI (Fig. 6d).

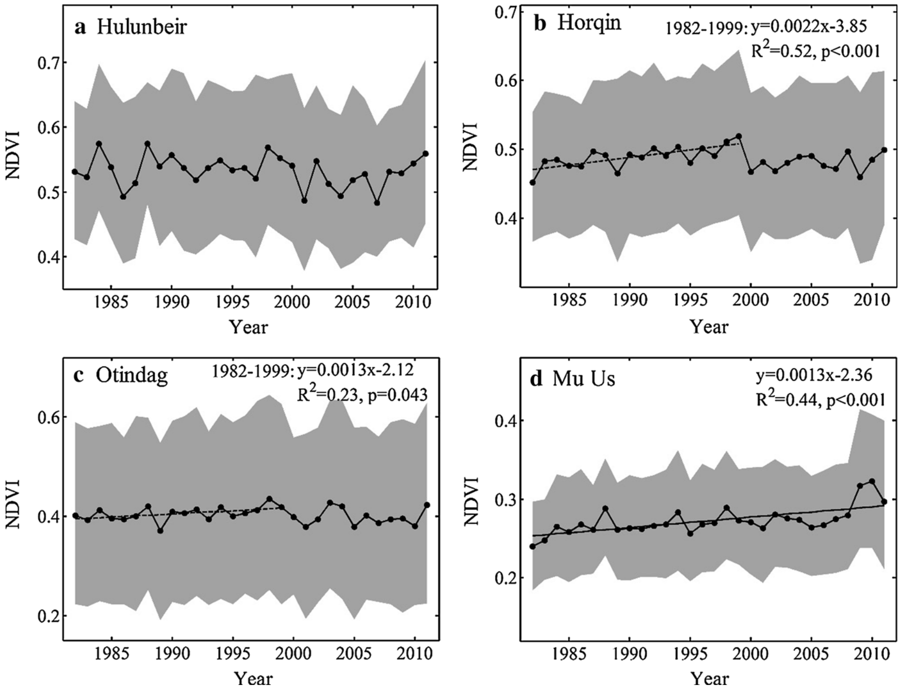

Fig. 3 Interannual variations of growing season (May–September) NDVI in the four mega-sandy lands. *Gray area* is the range of NDVI between 5 and 95 % quantile

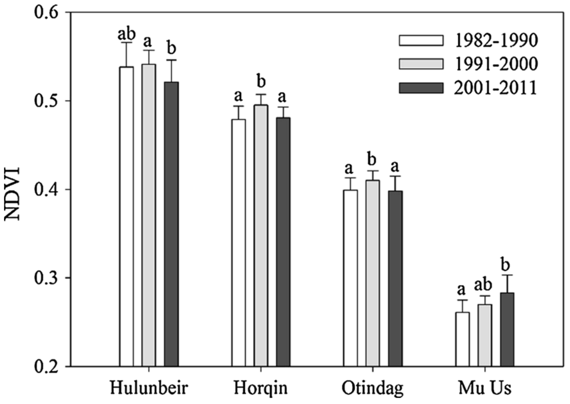

Fig. 4 Comparison of decadal-averaged growing-season (May–September) NDVI among the 1980s (1982–1990), 1990s (1991–2000) and 2000s (2001–2011) in the four mega-sandy lands. For each sandy land, *bars sharing a common letter* are not significantly different at 0.05 level

Further investigation with RESTREND analysis was applied to detect the impact of human activities on NDVI trends in the four mega-sandy lands. The cumulative precipitation over various periods (annual for Hulunbeir, May–September for Otindag and June–August for Horqin) was positively correlated with $NDVI_{max}$ in all sandy lands except Mu Us during 1982–2011, and thus we only analyzed trends of regression residuals in those three sandy lands. The residuals increased significantly in Horqin, while showed no trends in the other two (Fig. 7). The uptrend of residuals in Horqin suggested that the improvement of vegetation activity there might be attributed to anthropogenic factors over the past 30 years. No trends in Hulunbeir and Otindag indicated that the impact of human activities on vegetation changes were more complicated—human influenced vegetation changes in a good way in several years but in a bad way in other years, which could not be detected at regional scale for the whole study period.

However, no correlations between precipitation and growing-season or annual maximum NDVI in Mu Us implied that non-climatic factors might have contribution to the increase in NDVI. We compared interannual variation of growing-season NDVI and livestock number in Mu Us during 1987–2011 (Fig. 8). The livestock number is composed of numbers in Wushen Banner and Etuokeqian Banner, the main body of Mu Us (from Inner Mongolia Statistical Yearbooks 2012). The livestock number increased after 2002, and reached a peak in 2006. Meanwhile, both GIMMS NDVI and MODIS NDVI decreased from 2002 to 2006 even with different NDVI values.

Table 2 Comparison of decadal-averaged seasonal NDVI (spring, summer and autumn) in grassland during 1980s (1982–1990), 1990s (1991–2000) and 2000s (2001–2011) in the four mega-sandy lands

Sandy land	Spring (Mar–May)			Summer (Jun–Aug)			Autumn (Sep–Nov)		
	1980s	1990s	2000s	1980s	1990s	2000s	1980s	1990s	2000s
Hulunbeir	0.222	0.236	0.236	0.570	0.566	0.545	0.323	0.325	0.323
Horqin	0.212	0.213	0.206	0.502	0.522	0.501	0.300	0.307	0.298
Otindag	0.186	0.187	0.193	0.419	0.434	0.420	0.258	0.263	0.249
Mu Us	0.212	0.213	0.206	**0.268**	**0.275**	**0.288**	**0.170**	**0.179**	**0.188**

Grassland includes typical steppe, meadow steppe, desert steppe and meadow. The values in bold are summer and autumn grassland NDVI in Mu Us which persistently increased from the 1980s to the 2000s

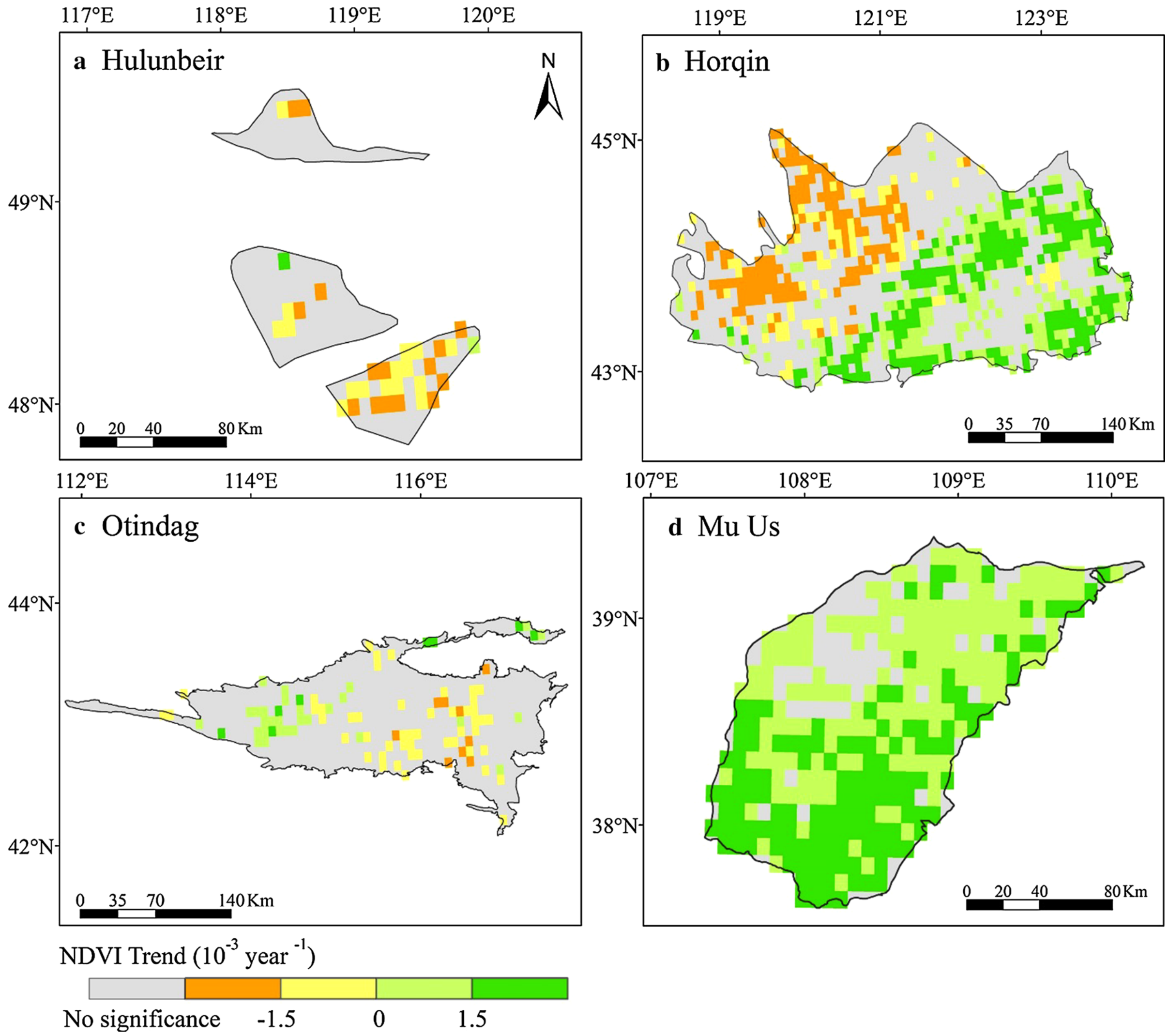

Fig. 5 Spatial patterns of growing-season (May–September) NDVI trend over 1982–2011 in the four mega-sandy lands

Table 3 Trends of climate factors (mean annual temperature, mean annual precipitation and mean annual wind speed), and correlation coefficients between NDVI and mean annual temperature (R_{NDVI-T}), mean annual precipitation (R_{NDVI-P}) and mean annual wind speed (R_{NDVI-W}) in the four mega-sandy lands during 1982–2011

Sandy land	Temperature (°C/year)	Precipitation (mm/year)	Wind speed (m/s year)	R_{NDVI-T}	R_{NDVI-P}	R_{NDVI-W}
Hulunbeir	0.031**	−4.182**	−0.014**	−0.235	0.677**	0.270
Horqin	0.042**	−1.568	−0.012**	0.081	0.314*	−0.122
Otindag	0.027**	−2.339	−0.018**	0.093	0.413**	−0.139
Mu Us	0.053**	−0.042	−0.009**	−0.135	0.163	−0.111

* $p < 0.1$, ** $p < 0.05$

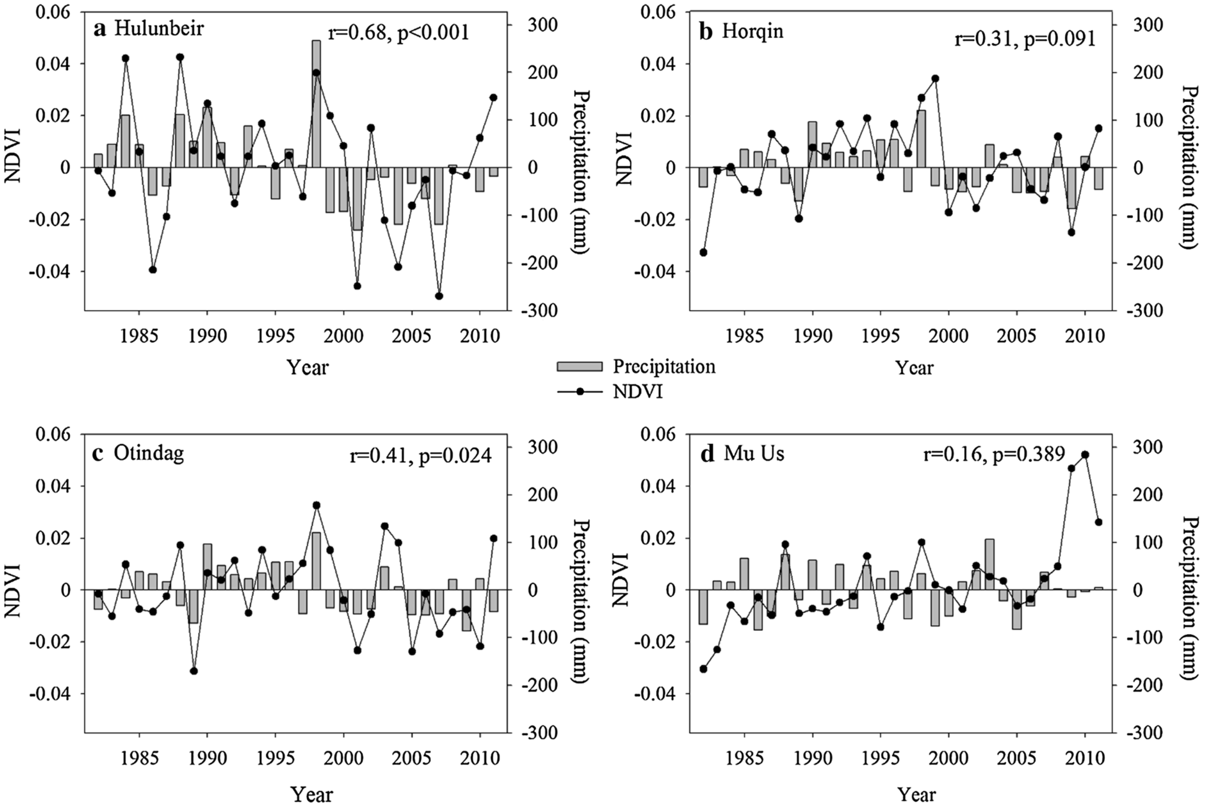

Fig. 6 Correlations between growing-season (May–September) NDVI anomalies and annual precipitation anomalies from 1982 to 2011 in the four mega-sandy lands

Discussion

Relationship between NDVI and desertification

Desertification expansion was observed in most areas of the four sandy lands prior to the 1980s. Then, the expansion rate slowed down in the late 1980s and early 1990s. Since 2000, the desertified area has stabilized in most sandy areas, and even decreased in certain local regions (Wu 2004; Liu and Wang 2007; Ao et al. 2010). By analyzing interannual variations of NDVI in the four mega-sandy lands over the past 30 years, we found that changes in NDVI were generally consistent with the desertification process. In Horqin and Otindag, NDVI increased significantly in the 1990s and peaked at the end of that decade, followed by a

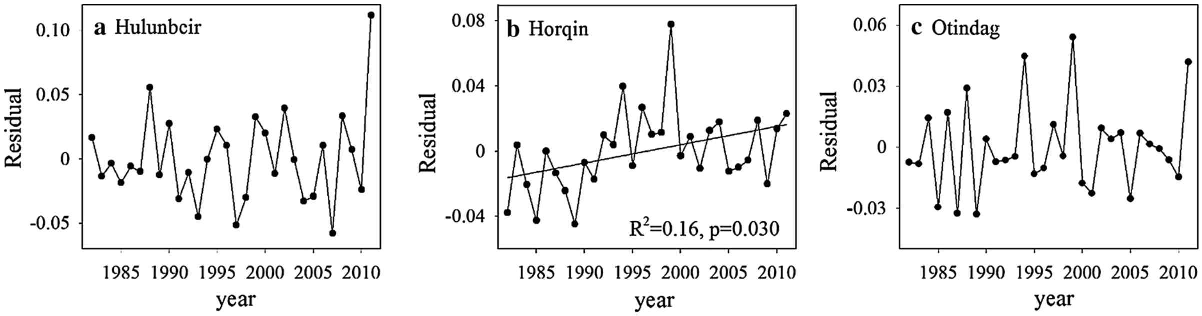

Fig. 7 The residual trends in Hulunbeir, Horqin and Otindag over 1982–2011

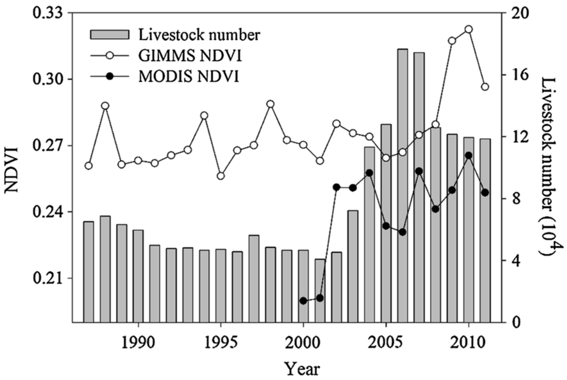

Fig. 8 Interannual variations of growing-season (May–September) NDVI and livestock number from 1987 to 2011 in Mu Us sandy land. Livestock number is composed of numbers in Wushen Banner and Etuokeqian Banner, the main body of Mu Us sandy land (from Inner Mongolia Statistical Yearbooks 2012)

decrease beginning in 2000 (Liu et al. 2010; Li et al. 2011). However, more details, such as vegetation structure and species composition, should be considered for comprehensive evaluation of desertification, since NDVI changes cannot fully reflect the land degradation in sandy lands, especially in areas with extremely poor vegetation cover (Mason et al. 2008; Herrmann and Tappan 2013). Lin et al. (2010) suggested that the significant changes of vegetation structure induced by increasing grazing intensities might be an early sign of desertification in desert steppe in Inner Mongolia.

Effects of climate change on NDVI

In arid and semiarid areas, vegetation activity is strongly affected by climate change, especially precipitation (Nicholson and Farrar 1994; Wang et al. 2001; Ichii et al. 2002; Fang et al. 2005). Our studies also showed that NDVI changes were highly correlated with the variations of precipitation in all sandy lands except Mu Us (Fig. 6). The results are coincident with previous studies (Zhang et al. 2011; Wu et al. 2013), which indicated that rainfall was the main driving factor for vegetation changes in sandy lands. Some studies showed that strong uptrends of temperature during the last decades might have aggravated the process of desertification in sandy lands (Yang et al. 2007). However, our results suggested no significant correlations between NDVI and temperature in all four sandy lands (Table 3).

In aeolian desertification areas, strong winds are recognized as one of the most important negative factors for vegetation growth, especially in drought season. Wind can constrain plant growth by burial and abrasion, losing soil, and interrupting natural processes of nutrient accumulation (Okin et al. 2001). Though no significant correlations were found between mean annual wind speed and growing season NDVI in all four sandy lands, some studies observed a significantly negative correlation between vegetation activity and spring sandstorms in eastern and central regions of Inner Mongolia (Zou and Zhai 2004).

Effects of human activities on NDVI

Human activities had a marked impact on vegetation changes in sandy lands, and was even the principal factor in some local regions. Many studies have ascribed desertification exacerbation in the early 1980s to human activities, including rapid population growth (Fullen and Mitchell 1994), overgrazing (Lin et al. 2010), excessive land reclamation, and continuous development of mining industry (Hu et al. 2005).

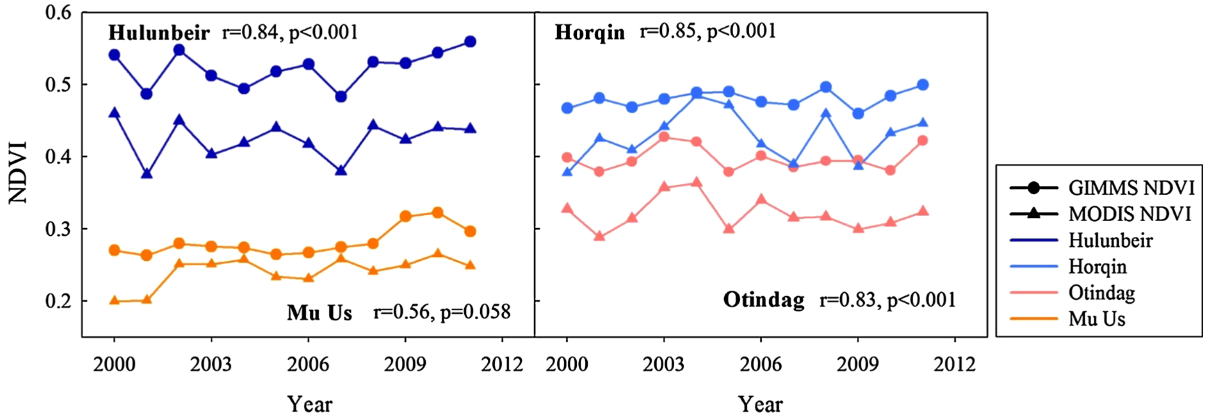

Fig. 9 Interannual variations of growing-season (May–September) NDVI from GIMMS and MODIS in the four mega-sandy lands, during 2000–2011

However, human activities were also responsible for the NDVI improvement in the sandy lands during the past 30 years. The uptrend of regression residuals in Horqin suggested a positive role of human activities in promoting vegetation activity during the past 30 years, especially in the southeastern part. The significant NDVI increase in southeast Horqin was mainly driven by the extent of cropland from the 1980s (Li et al. 2011) and the implement of ecological restoration projects from the late 1990s, such as the “Three-North Shelterbelt” and the “Grain for Green” projects (Zhang et al. 2012). Therefore, the impact of human activities on vegetation growth was bidirectional in most sandy areas.

No significant correlations between NDVI and climatic factors in Mu Us indicated that human activities might dominate the vegetation changes there. Our findings showed that the anthropogenic factors were principally responsible for the significant NDVI increase in most areas of Mu Us during the past 30 years, same with previous studies. For example, the area of crop cultivation, with well-established irrigation system, had increased by almost fivefold in Mu Us since 1978 (Runnstrom 2003). A series of ecological restoration projects implemented by local government, such as decreasing livestock numbers and fencing grasslands, had promoted rehabilitation of grasslands (Yan et al. 2012). In addition, large areas of afforestation since 1950s had greatly increased the area of woodland in Mu Us (Wu 2001), which had increased by 430 % from 1980s and covered 33.7 % area of Mu Us in 2000 (Fang et al. 2009).

Comparison of GIMMS NDVI with MODIS NDVI

The significant positive correlations between NDVIs from GIMMS and MODIS indicated that the two data had consistent interannual variations in all sandy lands (Fig. 9). We further compared the spatial pattern of NDVI trends from GIMMS and MODIS for the four sandy lands, and found a low correlation between the two NDVIs in certain local regions of Mu Us. The obvious differences appeared in northeastern and southern Mu Us, where shifting sand dune chains were densely distributed (Fig. 10). Within such sand dune chains, wetlands between sand dunes had more suitable conditions for vegetation growth, leading to much higher vegetation cover than its adjacent sand dunes (Department of Geography of Peking University et al. 1983). Unfortunately, the vegetation cover differences could hardly be identified in the 8-km GIMMS NDVI because of its coarse spatial resolution. The zonal distribution of uptrends of MODIS NDVI in southern Mu Us might be caused by this alternating distribution of sand dunes and dune wetlands. Our results indicated that the interannual variations of vegetation activity from GIMMS NDVI were reliable in the four mega-sandy lands. However, due to its coarse spatial resolution, GIMMS NDVI might fail to identify the differences of vegetation coverage at small scale in areas of complex terrain.

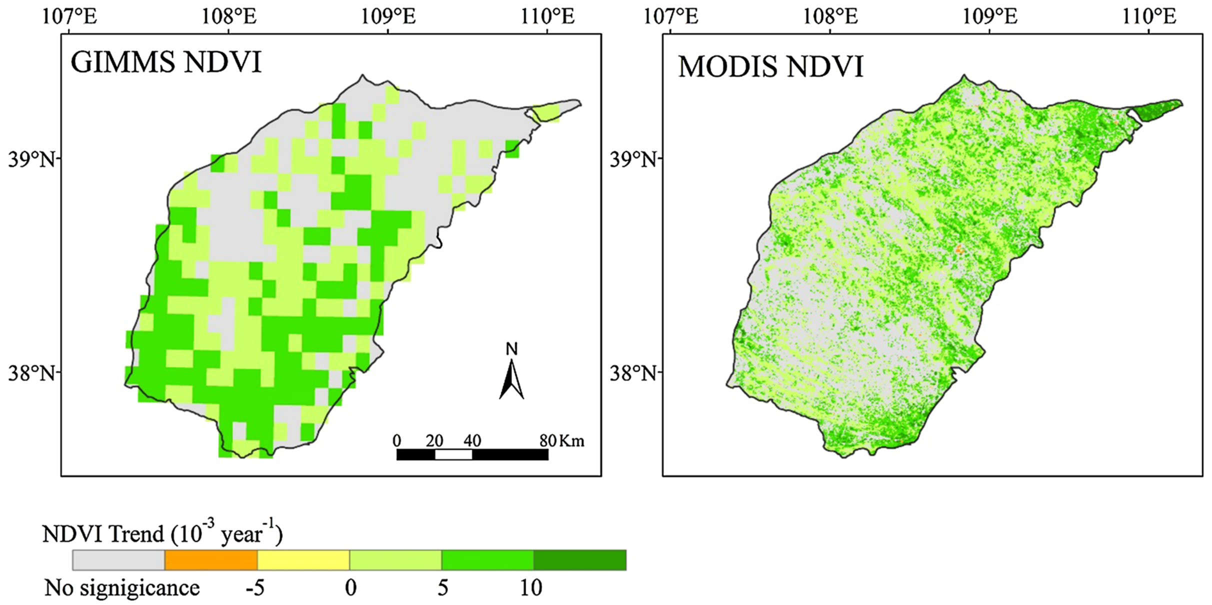

Fig. 10 Comparison of spatial patterns of growing-season (May–September) NDVI trend from GIMMS and MODIS in Mu Us, during 2000–2011

Concluding remarks

We analyzed spatiotemporal variations of vegetation activity in the four mega-sandy lands in Inner Mongolia, China, during 1982–2011. Conclusions regarding NDVI changes and factors affecting the changes in the study area are as follows.

1. There was an uptrend of growing-season NDVI in Mu Us, while no significant trends were in the other three sandy lands, where the growing-season NDVI maximized in the 1990s.
2. NDVI trends showed a clear spatial heterogeneity in the sandy lands. There were strong uptrends in northeast and south Mu Us and southeast Horqin, while the downtrends occurred in south Hulunbeir, northwest Horqin, and the grass-shrub ecotone in central Otindag.
3. NDVI trends were positively correlated with precipitation and uncorrelated with temperature and wind speed in all sandy lands except Mu Us. And the effect of human activities was only detected in Horqin by the RESTREND analysis, which suggested that improved vegetation activity there might be attributed to human activities during 1982–2011. Human activities were also responsible for the significantly increasing NDVI in Mu Us, especially the development of ecological restoration projects from the 1970s.
4. The comparison of GIMMS NDVI and MODIS NDVI verified the reliability of GIMMS NDVI for investigating interannual variations of vegetation activity in the four sandy lands. However, due to its coarse spatial resolution, GIMMS NDVI might have difficulties in identification of differences of vegetation coverage at small scale in areas of complex terrain.

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