Environmental Science & Technology
Article
pubs.acs.org/est

Drought Offset Ecological Restoration Program-Induced Increase in Vegetation Activity in the Beijing-Tianjin Sand Source Region, China

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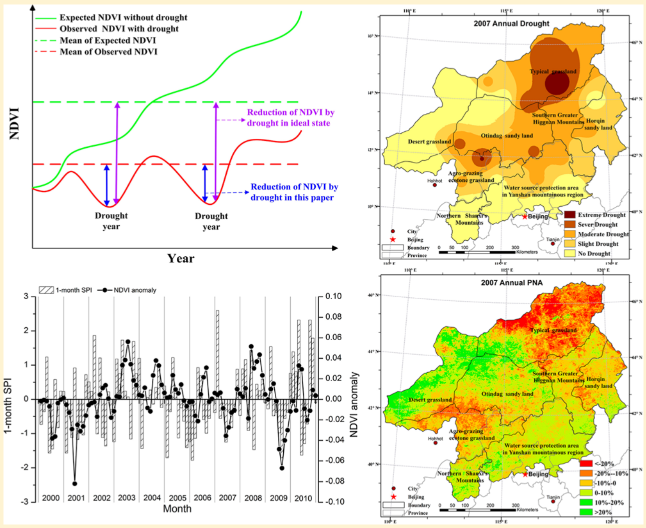
Ⓢ *Supporting Information*

ABSTRACT: To improve the ecological conditions, the Chinese government adopted six large-scale ecological restoration programs including 'Three-North Shelterbelt Project', "Grain for Green Project" and "Beijing-Tianjin Sand Source Control Project". Meanwhile, these ecologically vulnerable areas have experienced frequent droughts. However, little attention has been paid to the impact of drought on the effectiveness of these programs. Taking Beijing-Tianjin Sand Source Region (BTSSR) as study area, we investigated the role of droughts and ecological restoration program on trends of vegetation activities and to address the question of a possible "drought signal" in assessing effectiveness of ecological restoration program. The results demonstrate the following: (1) Vegetation activity increased in the BTSSR during 2000−2010, with 58.44% of the study area showing an increased NDVI, of which 11.80% had a significant increase at 0.95 confidential level. The decreasing NDVI trends were mainly concentrated in a southwest-to-northeast strip in the study area. (2) Drought was the main driving force for a decreasing trend of vegetation activity in the southwest-to-northeast regions of the BTSSR at the regional and spatial scales. Summer droughts in 2007 and 2009 contributed to the decreasing trend in NDVI. The severe and extreme droughts in summer reduced the NDVI by approximately 13.06% and 23.55%, respectively. (3) The residual analysis result showed that human acitvities, particularly the ecological restoration programs, have a postive impact on vegetation change. Hence, the decreasing trends in the southwest-to-northeast regions of the BTSSR cannot be explained by the improper ecological restoration program and is partly explained by droughts, especially summer droughts. Therefore, drought offset the ecological restoration program-induced increase in vegetation activity in the BTSSR.



1. INTRODUCTION

Severe ecological problems, such as desertification, sand storms, soil erosion, and wildlife habitat loss, are increasing in China during the past three decades.[1,2] To improve the environmental conditions of China and to reduce these problems' impacts, the Chinese government has initiated six large-scale ecological restoration programs including the 'Three-North Shelterbelt Project', the 'Beijing-Tianjin Sand Source Control Project' and the "Grain for Green Project".[3−6] Therefore, the environment of China has changed after the implementation of these large-scale projects. Vegetation change partly represents ecological environment change.[7,8] Increased trends in vegetation activity have been reported in China from 1982 to 2010 and large-scale afforestation and reforestation is the main factor for this increasing trend.[9,10] Moreover, vegetation growth is highly sensitive to the frequency and persistence of precipitation deficits or excesses in the arid and semiarid regions.[11−14] And drought is found to significantly affect vegetation change.[15,16] Recently, ecologically vulnerable areas such as Three-North Shelterbelt Project Region and Beijing-Tianjin Sand Source Region (BTSSR) have experienced frequent droughts. However, the impacts of ecological restoration program and drought on vegetation change are unclear in these ecologically vulnerable areas.

Received: August 23, 2013
Revised: August 28, 2014
Accepted: September 9, 2014
Published: September 9, 2014

dx.doi.org/10.1021/es502408n | *Environ. Sci. Technol.* 2014, 48, 12108−12117

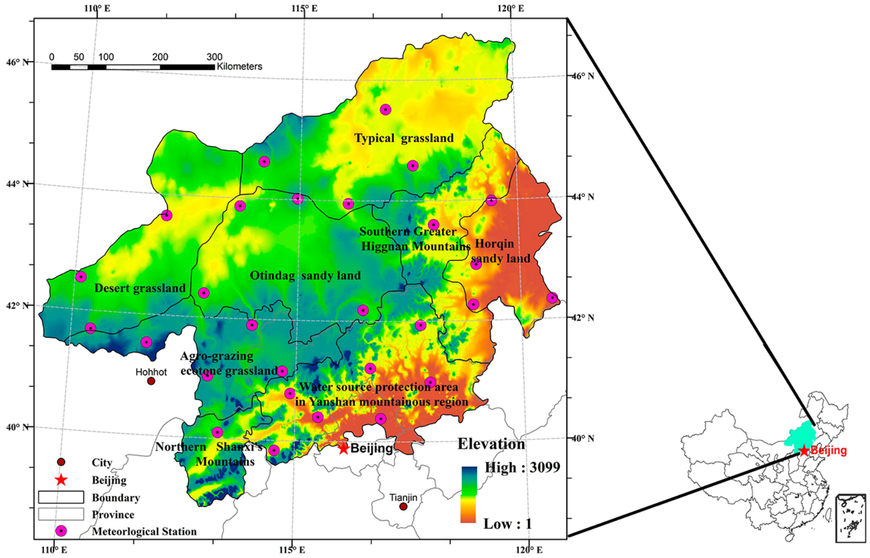


Figure 1. Location of the study area in China.

Furthermore, there is an ongoing debate about the effectiveness of national ecological restoration programs in China. On one hand, numerous Chinese researchers and government officials have claimed that ecological restoration programs had successfully combated desertification and controlled dust storms.[17−19] On the other hand, several experts have come to a shared view that ecological restoration programs in semiarid and arid regions may not work well.[20−22] Cao further asserted that afforestation could lead to increase ecosystem deterioration and wind erosion.[23] However, whether the decreasing trend of vegetation activity in these ecological vulnerable areas was indeed result from the improper ecological restoration program is unclear. Additionally, the role of drought in assessing the effectiveness of these programs is uncertain. Whether we should consider the effects of drought on vegetation change is unclear when assessing the benefits of ecological restoration programs.

To answer these questions, in this paper, we chose BTSSR as the study area, where the Chinese government implemented one of the six large-scale ecological restoration programs, named as the Beijing-Tianjin Sand Source Control Project since 2001. We choose this research region for following reasons: First, increased trends in vegetation activity have been reported. Intriguingly, there has been no obvious increasing trend over the past decade.[24] Second, the BTSSR has particularly suffered from drought. For example, an intense and prolonged drought affected several provinces (Shanxi, Hebei and Beijing) of the BTSSR in 2009.[25,26] Third, the Beijing-Tianjin Sand Source Control Program was completed at the end of 2010, and it is necessary to evaluate the effectiveness of this program.

The objective of this study is to investigate the role of drought and ecological restoration program on the trends of vegetation activity and to address the question of a possible "drought signal" in assessing effectiveness of ecological restoration program in BTSSR. Using observed MODIS NDVI from 2000 to 2010 and precipitation data from 1952 to 2010, first, we characterized spatiotemporal changes in NDVI and Standardized Precipitation Index (SPI) across BTSSR based on a linear regression algorithm at annual, seasonal and monthly scales. Second, we analyzed how drought has influenced vegetation activity and estimated the reduction on vegetation activity related to distinct regional droughts during the specific drought years. Finally, we separate the effects of extreme droughts and ecological restoration project on the NDVI to address the question of a possible "drought signal" in assessing the effectiveness of ecological restoration program.

2. DATA AND METHODS

2.1. Study Area. The BTSSR is bounded by the Damao Banner in Inner Mongolia on the west, Ping Yuan County in Hebei Province on the east, Dai County in Shanxi Province on the south and the Dong Ujimqin Banner in Inner Mongolia on the north (Figure 1a). The region's geographical coordinates are 109°30′ ∼ 119°20′E and 38°50′ ∼ 46°40′N. There are 75 counties (banners, cities or districts) in the Beijing, Tianjin, Hebei, Shanxi and Inner Mongolia provinces in this region and its total area is 458 000 km^2

This area's topography includes plains, mountain and plateau. The plains are located in the southeast and are part of the plain of the Haihe River; the west, northwest, and north of this area are located in the central Inner Mongolian Plateau, where the landform has a declining slope from west to east; the mountains are in the middle of the plain and plateau and include the northern Taihang and Yanshan Mountains and the southern Greater Higgnan Mountains from southwest to northeast. The Otindag and Horqin Sandy Lands are located in the central and eastern areas. The variations in landforms in this area cause climate differences, including two climatic zones and five climatic regions. The annual average temperature in this area is from 4 to 7.5 °C. The total annual precipitation is from 250 mm to 470 mm.[27]

To analyze the benefits of the ecological restoration program, Gao divided the BTSSR into eight subareas:[27] desert grassland subarea (Desert grassland); typical grassland (Typical grassland); Otindag sandy land (Otindag); southern Greater Higgnan Mountains (Greater Higgnan); Horqin sandy land (Horqin); agro-grazing ecotone (Agro-grazing ecotone); northern Shanxi's mountainous (Northern Shanxi) and water source protection area in the Yanshan mountains (Yanshan). These subareas were defined based on the complex climate, landform, soil and vegetation of the BTSSR. In this paper, we adopt the same divisions (Figure 1).

2.2. Data Set. The monthly NDVI data, with a 1-km spatial resolution covering the period from 2000 to 2010, were derived from MODIS from NASA's Earth Observing System. The MODIS monthly NDVI data were obtained using the maximum value composite (MVC) method, which minimizes cloud contamination, atmospheric effects and solar zenith angle effects.[28] In this paper, similar to Stayback and Wang, a NDVI threshold of 0.05 was used to exclude bare and sparsely vegetated area.[29,30] Monthly precipitation and temperature data from 28 meteorological stations distributed throughout the BTSSR (Figure 1) from 1952 to 2010 were obtained from the Chinese National Meteorological Center.

2.3. Standardized Precipitation Index (SPI). In this study, drought events were evaluated based on the standardized precipitation index (SPI) developed by McKee.[31] The SPI is calculated by fitting historical precipitation data to a Gamma probability distribution function for a specific time period and location, and transforming the Gamma distribution to a normal distribution with a mean of zero and standard deviation of one. The classification of drought based on the SPIs is given in Table 1.[32,33] We used 1-month, 3-month, and 12-month SPIs to represent monthly, seasonal, and annual drought conditions, respectively. More information on computing the SPI was shown in the Supporting Information (SI) (SI text S1).

Table 1. Classification of Drought Intensity

SPI value	intensity
$-1.00 < \text{SPI} \leq -0.5$	slight drought
$-1.50 < \text{SPI} \leq -1.00$	moderate drought
$-2.00 < \text{SPI} \leq -1.50$	severe drought
$\text{SPI} \leq -2.00$	extreme drought

2.4. Methods. A linear regression method was applied to detect and analyze trends in the time series. The slope of the regression indicated the mean temporal change in the studied variable, such as NDVI and SPI. Positive slopes indicate increasing trends, while negative slopes indicate decreasing trends.[34−36]

The residual analysis method was used to separate the effects of drought and human activities on NDVI.[14] First, we performed linear regression calculations between the annual SPI and the annual NDVI for each pixel. With the linear regression describing the expected NDVI, the difference between the observed NDVI and the regression predicted NDVI was calculated for each pixel. The differences are referred to as residuals, which indicate vegetation change response not due to drought effects. The negative residual indicates an area experiencing human-induced degradation while the positive residual indicates human-induced improvement. In this paper, the sum of residual from 2001 to 2010 is investigated to analyze the effects of human activities on vegetation dynamics in the BTSSR.

3. RESULTS

3.1. Spatiotemporal Trends in Vegetation activity and SPI. *3.1.1. Regional Trends in the NDVI and SPI.* NDVI and SPI were used to characterize vegetation and drought conditions in the BTSSR, respectively. The NDVI showed a complex interannual variation over last 11 years, with an overall increasing trend of 0.0006 yr^{-1} ($R = 0.16$, P=0.65) (Figure 2a). However, the overall increasing trend of NDVI was not statistically significant. Specifically, the NDVI showed an increasing trend in the first phase (2001−2005), whereas it was likely to follow multiyear fluctuation in the second phase (2006−2010), with a peak in 2008 and a valley in 2009. The lower value in 2007 and 2009 may have contributed to the nonsignificant increasing trend of NDVI in the BTSSR.

Similar to the annual NDVI trend, the annual SPI from 2000 to 2010, on average, displayed an increasing trend of 0.031 yr^{-1} (Figure 2a). There was also no significant trend in the SPI ($R = 0.13$, $P = 0.71$). The increased SPI was parallel with increased NDVI. In 2003, 2004, 2008, and 2010, the NDVI was relatively high, coinciding with the SPI peaks. Meanwhile, the NDVI minima of 2001, 2007, and 2009 correspond to the minima of the SPI over these years. Moreover, from an annual perspective, we found that there were 5 dry years (2000, 2001, 2005, 2007, and 2009) for the entire BTSSR based on the 12-month SPI($\text{SPI} < -1$) (Figure 2a). Obviously, the study area had experienced severe drought in 2009. Meanwhile, the lowest NDVI among 11 years was also found in 2009.

Furthermore, the interannual variations of the 1-month SPI and the growing season NDVI anomalies (March to November) were analyzed in the BTSSR over the last 11 years (Figure 2b). The patterns of SPI fluctuation corresponded well to that of the NDVI. Regionally, the negative monthly NDVI anomalies were mainly caused by droughts, especially in the middle and latter of the growing season in 2007 and 2009. Therefore, drought is likely to be the main factor for decreased NDVI across BTSSR.

3.1.2. Spatial Patterns of NDVI and SPI Trends. The interannual variations of regional average NDVI and SPI could not illustrate the true vegetation and drought conditions at the spatial scale. The trend of NDVI showed obvious heterogeneity across BTSSR (Figure 3a), which inceased in the majority of areas in the YanShan, Northern Shanxi, southern Greater Higgnan, southern Horqin, desert grassland and southwest typical grassland (green). However, the decreasing trends of NDVI occurred in most areas of agro-grazing ecotone (located in the southwest of the study area), southern Otindag (located in the center of the study area), northern Greater Higgnan and southeast of typical grassland (located in the northeast of the study area). These regions with decreasing trend of NDVI were mainly concentrated in a southwest-to-northeast strip in study area (red). Statistically, NDVI increased in 58.44% of the total study area over the 11 years, 11.80% of which was significant at 0.95 confidential level. Additionally, we found that only 2.48% of the total study area showed a significant decrease at 0.95 confidential level.

The spatial pattern of the annual SPI trend also showed great geographical variability from 2000 to 2010 (Figure 3b), with an increasing tendency in most areas of the BTSSR (green) and a decreasing trend in part of the areas (red). Again, the trend of NDVI and SPI from 2000 to 2010 matched quite well. The decreasing trends of the SPI were mainly within a southwest-to-northeast band in the study area. To further evaluate the relationship between NDVI and SPI trends, the trends of NDVI and SPI were extracted from 28 meteorological stations. The NDVI trends at the 28 meteorological stations were significantly and positively correlated with the trends in the SPI ($p = 0.001$) (Figure 3c). To analyze effects of drought on NDVI trends, the correlation coefficient between NDVI and SPI was calculated for each pixel (Figure 3d). NDVI was positively correlated with SPI in most areas, suggesting that the

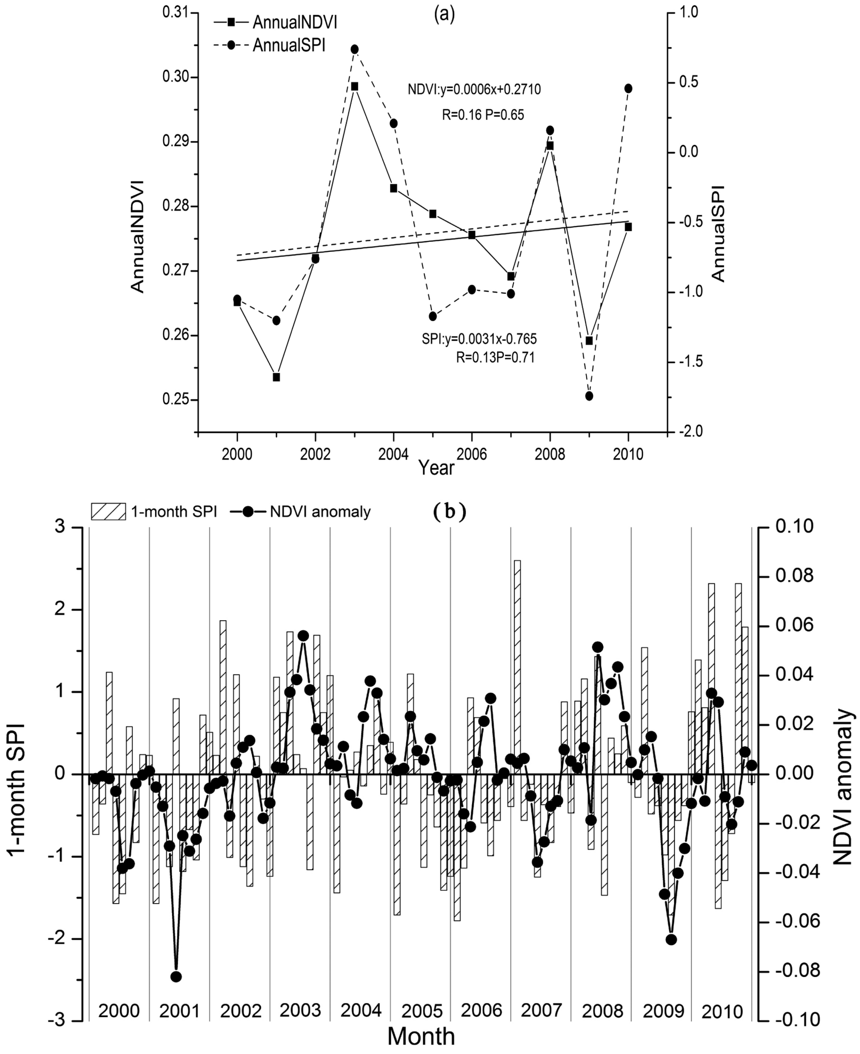


Figure 2. Interannual variations in the annual NDVI and SPI (a) and in anomalies of monthly NDVI and monthly SPI (b) in the BTSSR during 2000–2010.

possible effects of drought on decreased NDVI in southwest-to-northeast area. The values of 0.602 and 0.521 for correlation coefficients in Figure 3d correspond statistically to at 0.95 and 0.9 confidential levels, respectively.

To explore whether this linkage at the seasonal scale was consistent with that at the annual scale and to more clearly recognize the contribution of each season to the annual NDVI and SPI trends, we also discuss the trends in the NDVI and SPI in three seasons: spring (March to May), summer (June to August) and autumn (September to November).We found that the summer drought, rather than spring drought and autumn drought, was the main driving force for a decreasing trend in NDVI in most of southwest-to-northeast regions (more information see SI text S2).

3.2. Drought Impacts on Vegetation Activity in BTSSR. To analyze the effects of drought on NDVI trends, in this section, first we identified the drought in BTSSR from 2000 to 2010 and we found that the BTSSR was experiencing severe droughts in 2001, 2005, 2007, and 2009 (more information see SI text S1). Then we discussed the drought-induced impact on the NDVI in the 4 drought years. The spatial drought patterns and the annual percentage of NDVI anomalies in the four drought years are shown in Figure 4. First, the spatial patterns of the percentage of NDVI anomalies in those 4 years highlight the regions with the most severe droughts. Second, the reductions in the NDVI were significantly different among the different drought classification levels. In 2007, for example, the moderate drought occurred in the Otindag sandy land, where the NDVI was reduced by less than 10%. Severe and extreme droughts occurred in the typical grassland, coinciding with an NDVI anomaly of more than 20%.

However, in 2001, the spatial patterns of drought did not match quite well with those of NDVI (Figure 4). For example, the NDVI in Northern Shanxi decreased, while those regions did not experience the drought. Because the ecological restoration program was planned to be initiated in 2001, the decreased NDVI in 2001 also likely be associated with improper human activities. Meanwhile, note that the linkage between the regional average NDVI and SPI in 2005 (Figure 2a) was not significant. The drought in 2005 occurred in desert grassland (Figure 4), where the NDVI was smaller than the NDVI in other regions. Hence, the linkage between the regional average NDVI and SPI in 2005 was not significant, while the spatial patterns of NDVI and drought in 2005 matched quite well (Figure 4).

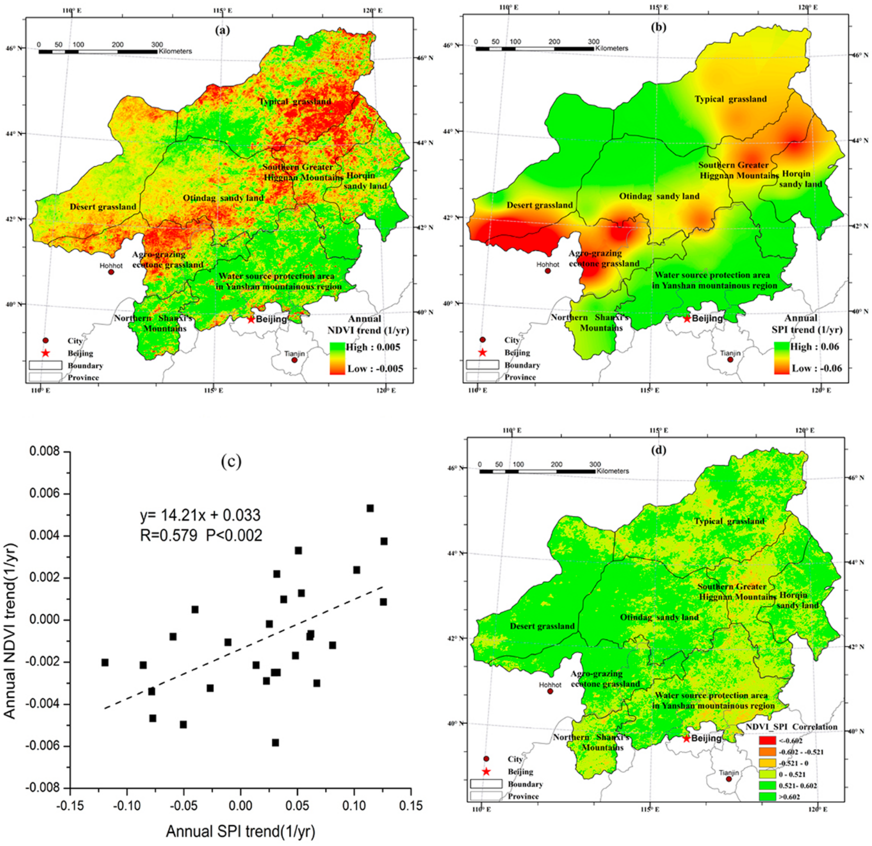


Figure 3. Spatial patterns of annual mean NDVI trends for each grid cell (a), spatial patterns of annual SPI trends for each grid cell(b), the scatter between the NDVI and SPI trends at 28 meteorological stations (c) and the correlation between the NDVI and SPI for each grid cell (d) in the BTSSR from 2000 to 2010.

The effects of drought on the NDVI were analyzed at the seasonal scale in the typical drought years. We also found that the spatial patterns of seasonal drought were correlated with the spatial patterns of percentage of NDVI anomalies, further confirming that the reduced NDVI was caused by droughts. The summer droughts in 2007 and 2009 occurred mainly in a southwest-to-northeast strip in the study area, which implies that the summer droughts in these two years result in the decreasing NDVI trend in these regions. (For more information see SI text S3).

3.3. Residual Analysis. The spatial pattern of NDVI residual reveals that the majority areas of BTSSR have experienced human-induced improvement (Figure 5). The improved areas were mainly in the YanShan, Northern Shanxi, southern Greater Higgnan, Horqin and typical grassland (green). The ecolgical restoration program is the main human activity in these regions, such as enclosure of grassland, conversion of cropland to forest or grassland (i.e., grain for green), reforestation and afforestation by aerial seeding or closing hill and grassland managements. The unchanged areas were mainly in the southeast of Otindag sandy and the west of desert grassland. The negative effects of unreasonable human acitivities may offset the postive effects of ecolgocial restoration program on vegetation change in these regions. Also, the negative NDVI residuals were mainly in the center of Otindag sandy, the northeast of desert grassland and the center of agro-grazing ecotone (red and yellow). In these areas, the main negative human activities maybe overgrazing and reclamation. Statistically, 45.94% of the total study area experienced human-induced improvement over the 11 years, 12.04% of which was significant. The vegetation activities were unchanged in the 24.58% of the BTSSR. Additionally, we found that only 4.36% of the total study area showed a significant human-induced degradation. Moreover, we can find the human activities result in increasing trend of NDVI in some areas of southwest-to-northeast region, such as the southeast of typical grassland, where the decreaed NDVI was caused by drought. Consequestly, the residual analysis showed that human activties paly a postive role on the increased NDVI in the BTSSR from 2000 to 2010 and that drought was the main driving force of decreased NDVI in southwest-to-northeast area. Therefore, severely droughts offset ecological restoration program-induced increase in vegetation activity in the BTSSR.

3.4. Drought-Induced Reduction in NDVI. From Figure 4 and Figure 5, most areas of severe and extreme droughts (SPI < -1.5) in 4 drought years were mainly experiencing human-induced improvement in the BTSSR. We speculate that the human activity-induced reduction in NDVI only accounted for a small proportion of the decreased NDVI and the drought-induced reduction in NDVI was the main cause of the decreased NDVI. We calculated the mean percentage of NDVI anomalies for different drought classification levels to further analyze the reductions of drought on NDVI. The mean percentage of the NDVI anomaly (MPNA) was defined as the average of the percentage of NDVI anomaly for all grid cells in one drought classification level. Table 2 shows the mean percentage of NDVI anomalies and the percentage of drought area (PNA) for different drought classification levels at the

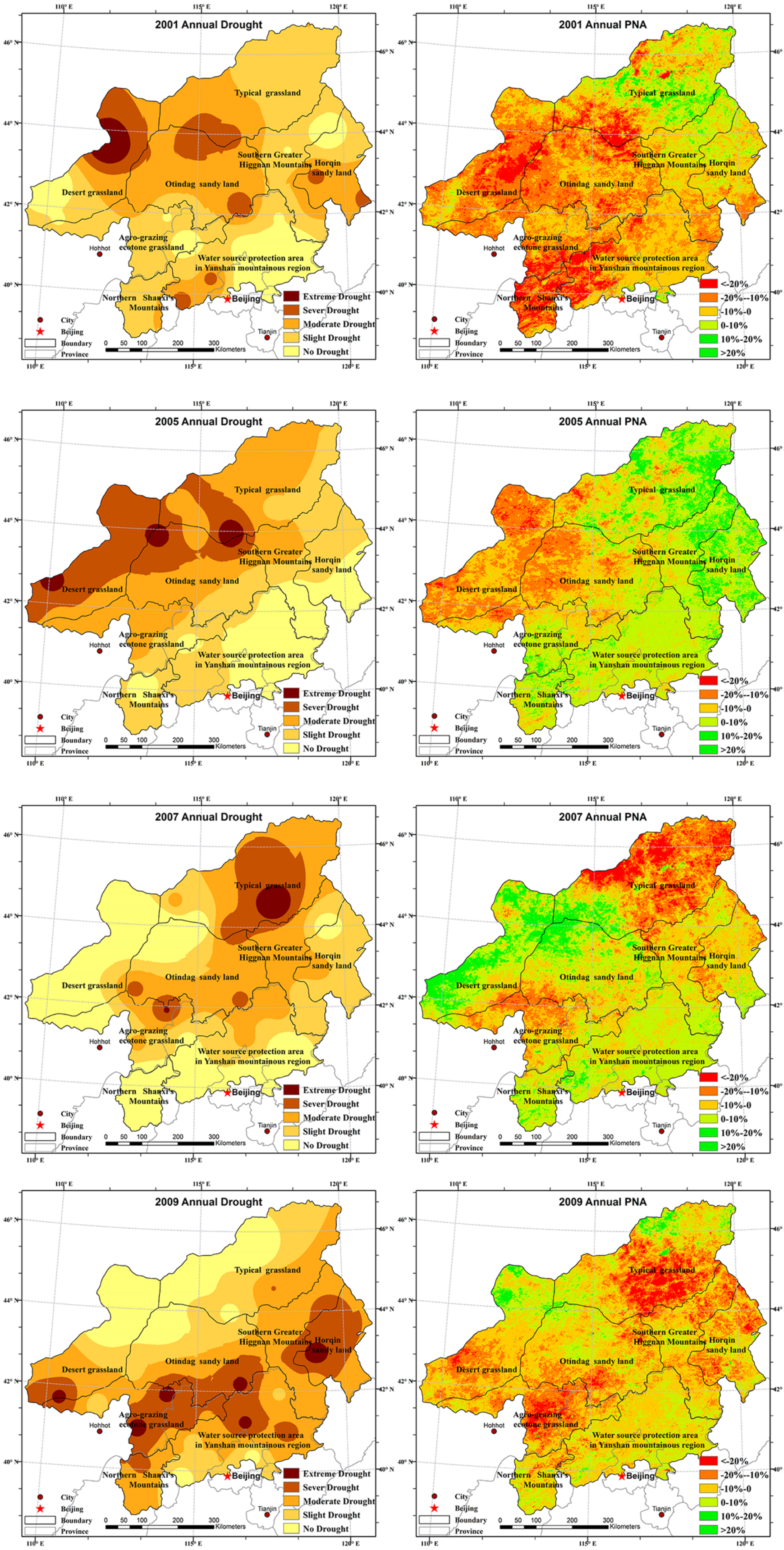


Figure 4. Spatial patterns of drought calculated based on the 12-month SPI and spatial patterns of the percentage of NDVI anomalies in the 4 drought years (2001, 2005, 2007, and 2009). "PNA" in the figure is the Percentage of NDVI Anomaly.

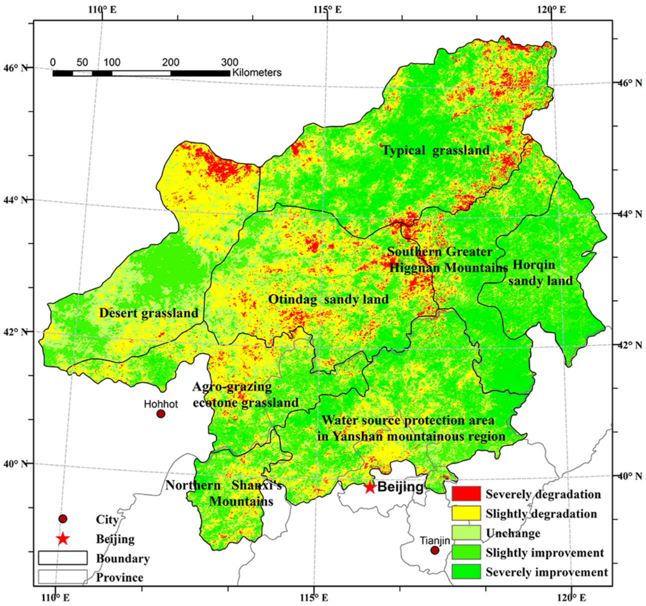


Figure 5. Spatial pattern of the sum of residual from 2001 to 2010 in the BTSSR.

annual and seasonal scales. The mean percentages of NDVI anomaly were significantly different among the drought intensity. Overall, the reduction in NDVI was more serious with increasing drought intensity. In 2009, for example, the moderate, severe and extreme drought reduced the NDVI by 6.68%, 8.23% and 9.27%, with drought areas of 37.17%, 19.31%, and 2.16%, respectively.

In this paper, we focused on the impacts of the combination of severe and extreme drought (SPI < −1.5) on NDVI. The highest percentage of severe and extreme drought area was 24.06% in 2009; the others were in 2005 (21.47%), 2007 (12.06%), and 2001 (11.89%). Interestingly, the MPAN in those 4 years were 14.78% (2001), 12.03% (2007), 8.44% (2005) and 8.36% (2009). Obviously, the reduction in NDVI was more serious with decreasing drought area in the 4 years. The reasons for this phenomenon might be the following: (1) Different vegetation types responded differently to the droughts. The larger drought areas influence more vegetation types than the smaller drought areas. For example, in 2005, the drought occurred in the desert grassland, where the vegetation type was mainly grass, while in 2009, the drought occurred in the agro-grazing ecotone, Yanshan, southern Greater Higgnan and Horqin sandy land, where the vegetation types were mainly cultivation, forest, shrubs, and grass. (2) The onset of drought was very important to the reduction of vegetation activity.

Additionally, the drought-induced reduction of the NDVI was analyzed at the seasonal scale in the drought years. We have found that the summer droughts in 2007 and 2009 were the main driving force in the decreasing NDVI trend in southwest-to-northeast regions. Hence, we analyzed the effects of reductions of severe and extreme summer drought on NDVI in these two years. Specifically, the percentages of summer drought areas in 2007 and 2009 were 8.11% and 22.48%, which led to a decreased NDVI of 18.29% and 13.40%, respectively. Finally, the summer severe drought reduced the NDVI by 16.71%, 9.94%, and 12.54% in 2005, 2007, and 2009, respectively, and the summer extreme drought reduced the NDVI by 27.99%, 20.61%, and 22.06% in 2005, 2007, and 2009, respectively (Table 2). Therefore, the severe and extreme summer drought in those years reduced the NDVI by approximately 13.06% and 23.55%, respectively.

3.5. Impact of other factors on NDVI.

3.5.1. Temperature. Temperature change is one of the main drivers of the interannual variation in vegetation activity in China.[10] We investigated the interannual variation of temperature and NDVI during 2000−2010 in the BTSSR (SI Figure S4). We found that temperature was not the main driving force of vegetation dynamics in the BTSSR (more information see SI Text S4). Our finding is consistent with many previous studies. For example, Pei[37] found that precipitation, rather than mean temperature and maximum temperature, was the dominant climatic factor influencing NDVI in the BTSSR. Zhao[38] also found that the NDVI was positively correlated with precipitation in the arid and semiarid region in China.

3.5.2. Land Use Change. The Beijing-Tianjin Sand Source Control Project is a huge ecological restoration effort with

Table 2. Drought-Induced Reduction in NDVI for Different Drought Density at the Annual and Seasonal Scales

		annual		spring		summer		autumn	
year	drought	MPNA	PDA	MPNA	PDA	MPNA	PDA	MPNA	PDA
2001	moderate	−9.86%	31.05%	−11.59%	31.50%				
	severe	−14.61%	10.06%	−13.22%	11.17%				
	extreme	−15.76%	1.83%	−14.50%	2.50%				
	SPI < −1.5	−14.78%	11.89%	−13.45%	13.67%				
2005	moderate	−1.34%	31.17%			−9.78%	21.42%	−6.25%	42.60%
	severe	−8.60%	19.31%			−16.71%	13.06%	−1.50%	10.50%
	extreme	−6.99%	2.16%			−27.99%	0.67%	−0.87%	2.56%
	SPI < −1.5	−8.44%	21.47%			−17.26%	13.73%	−1.38%	13.06%
2007	moderate	−5.50%	29.42%			−12.67%	35.38%		
	severe	−11.50%	10.44%			−9.94%	6.60%		
	extreme	−15.41%	1.62%			−20.61%	1.51%		
	SPI < −1.5	−12.03%	12.06%			−18.29%	8.11%		
2009	moderate	−6.68%	37.17%			−11.34%	39.67%		
	severe	−8.23%	21.94%			−12.54%	20.45%		
	extreme	−9.70%	2.12%			−22.06%	2.03%		
	SPI < −1.5	−8.36%	24.06%			−13.40%	22.48%		

MPNA: Mean percentage of NDVI Anomaly PDA: Percentage of Drought Area.

some key measures, which include conversion of cropland to forest/grass, reforestation, and afforestation by aerial seeding/closing hill, integrated watershed management and ecological resettlement. Therefore, land use has changed greatly since the ecological project was implemented in the BTSSR. There is no doubt that land use change has large effects on the vegetation dynamics. We analyzed the NDVI change before and after different key measures and polices in typical Banner and County. After these key measures, the NDVI are increased in the County and Banner level (more information see SI text S5). With the field investigation data, Zhao found that the biomass was increasing from 2005 to 2010 after the conversion of cropland to forest in Duolun country, which is located in the south of Otindag sandy region.[39] Furthermore, reforestation and afforestation by aerial seeding or closing hills can also improve vegetation activity in the semiarid region.[40]

3.5.3. Grassland Management. Grassland managements, including enclosure of grassland, grazing prohibition, grazing rotation or grazing rest, also had great effects on vegetation change. Because it is difficult to characterize these policies with quantitative indicators, we used the number of livestock at the end of a year to indirectly represent these measures at county level. We also found that the NDVI was increasing after these key policies (more information see SI Text S6). Numerous studies have shown that enclosing grasslands can alter vegetation species composition and improve grassland productivity.[41−43]

3.5.4. Human Disturbance. Unreasonable human activities were another driving force of vegetation change in the BTSSR. To investigate the vegetation change, we carried out two large-scale field investigation surveys (SI Figure S8). And we found that unreasonable human activities such as the reproduce of overgrazing reduced the NDVI only in small areas. However, large-scale unreasonable human activities did not appear in large areas in the BTSSR, where the NDVI was decreasing. Therefore, drought was the main driving force of the decreased NDVI in southwest-to-northeast areas of BTSSR.

4. DISCUSSION

4.1. Drought-Induced Decreased Vegetation Activity in BTSSR. Positive NDVI trends were found in most areas BTSSR (58.44% of the total area and 11.80% at the 0.95 confidential level) over the past decade.[24,44] However, the overall increasing trend of NDVI was not statistically significant and the spatial patterns of the NDVI trend presented a very complex pattern in response to climate change and human activities.[24] The decreasing trends of NDVI were mainly concentrated within a southwest-to-northeast strip across the BTSSR. Currently, the most widely accepted explanation for these decreasing trends is improper human activities, such as overgrazing[27] or improper ecological restoration program.[22] However, our results demonstrate that drought in the study area was the main factor for that reduced the NDVI.

The spatiotemporal patterns in vegetation activities co-incided with those in the SPI. The decreased trend of NDVI in the southwest-to-northeast regions was mainly caused by droughts, especially by summer droughts in 2007 and 2009. Our finding is consistent with many previous studies, which have shown that large-scale droughts reduced vegetation activities based on experimental methods,[45] satellite observations[46] and carbon process models.[47,48] Specifically, our results show that the BTSSR experienced intense droughts in 2001, 2005, 2007, and 2009 and the decreasing trend of NDVI result from summer droughts.[49,50] The summer drought in 2009, which was reported as the driest year in the last three decades,[27] played a significant role in reducing the NDVI (southwest-to-northeast strip). Barriopedor analyzed the causes of the 2009−2010 drought and its impacts on vegetation in China. They found that the NDVI was severely affected by the extreme summer droughts, especially in northern China (particularly in the BTSSR).[26] Some mechanisms can contribute to these findings as follows. First, drought is found to significantly affect vegetation change, such as limiting photosynthesis and altering vegetation respiration. Second, severe drought can lead to a reduction in vegetation greenness and can affect vegetation mortality. Third, drought may also result in secondary natural disasters, such as fire, which has also been recognized as a major cause of disturbance of vegetation dynamics. If drought events continued as predicted,[50] they will reduce the vegetation activity and may exacerbate ecosystem degradation in the BTSSR.

4.2. Drought-Induced Reduction in NDVI in Ecological Restoration Program. The severe drought and extreme drought in summer reduced the NDVI by approximately 13.06% and 23.55% in the BTSSR, respectively. Our finding is also consistent with Zhang's research.[51] They found that drought reduced vegetation greenness in southwestern North America and the drought-induced reduction of vegetation greenness were 16% in shrublands and 21% in grasslands in the severe droughts years. However, the drought-induced reduction in NDVI in ecological restoration program region was very complicated. Figure 6 shows the sketch map of drought-induced reduction in NDVI in ecological restoration program region. In general, we note that if there is no drought, the vegetation activity will increase in ideal state in ecological project region, as described by the green solid line. And then the mean of expected NDVI in the specific period was shown by the green dotted line. However, due to the effect of many droughts on the NDVI, the observed NDVI was decreased, as shown by red solid line and the mean of observed NDVI was showed by red dotted line. We choose the NDVI anomaly to reveal the effects of drought on vegetation. Therefore, in a drought year, the difference between green dotted line and red

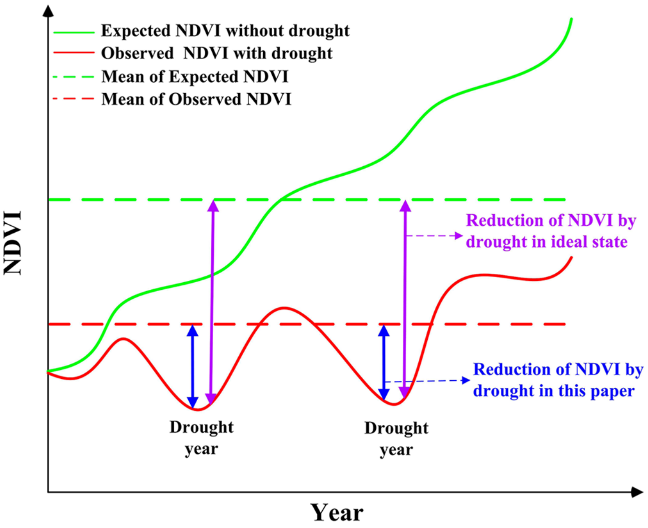


Figure 6. Sketch map of drought-induced reduction in NDVI in ecological restoration program region.

solid line represents to drought-induced reduction of NDVI in the ideal state (the purple arrow lines). The difference indicates that vegetation change response due to drought effects in the ideal state. However, in this paper, the estimation of the reduction NDVI by drought was showed by the blue arrow lines. From Figure 6, we can see that the reduction of NDVI by drought in observed state was smaller than that in ideal state. Hence, the reduction of severe and extreme drought on the NDVI in summer should be greater than 13.06% and 23.55% in the BTSSR.

In this paper, we tried to examine the effectiveness of the ecological restoration program with a focus on the variation in the NDVI. We found that the NDVI increased after the implementation of the project. Although the trend of increase is not significant, these changes cannot be explained by improper ecological restoration programs; these changes must be partly explained by the several severe droughts that occurred in the past decade. The residual analysis result showed that human acitvities, particularly the ecological restoration programs, had a postive impact on vegetation change. Therefore, the decreased NDVI in some areas cannot be used as the evidence to support claims that the ecological restoration program failed in the BTSSR. However, the role of drought in assessing the effectiveness of ecological restoration programs in other program regions is also uncertain. For example, Cai found that the vegetation activity was increasing in “Three North Shelterbelt Project” region during 1982−2000. He also found that, in the 45.20% of total area, the human activities play a negative role in the restoration of ecological environment.[8] However, whether the decreasing trend of NDVI was induced by drought is uncertain. In future, this interesting topic will be analyzed in other five ecological restoration program regions.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

This Supporting Information includes seven texts: (1) detail of the standardized precipitation index (SPI) algorithm and the drought identification in the BTSSR, (2) the spatial patterns in the NDVI and SPI trends at the seasonal scale, (3) the impact of drought on the NDVI at the seasonal scale, (4) the trend of temperature and NDVI, (5) the impact of land use change on the NDVI at the country level, (6) the impact of grassland management on NDVI at the country level and (7) the route of two large-scale field investigation surveys. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

We are grateful to the Editor and anonymous reviewers of this paper. This research received financial supports from the National Natural Science Foundation of China (No. NSFC 41171403), National Natural Science Foundation of China (No. NSFC 41401643), Science & Technology Pillar Program of Shanxi Province (No.20121101011), and the Fundamental Research Funds for the Shanxi University (No. 020751801001).

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