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ORIGINAL ARTICLE

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Aeolian desertification from the mid-1970s to 2005 in Otindag Sandy Land, Northern China

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Abstract Aeolian desertification in Otindag Sandy Land has expanded dramatically during the past 50 years. This research explored processes and causes of aeolian desertification in the study area. The results showed that aeolian desertification development in Zhenglan Qi of typical region located at the center in the study area can be divided into three stages including rapid occurrence before 1987, parts of rehabilitation and most of deterioration from 1987 to 2000 and little rapid rehabilitation occurrence from 2000 to 2005, according to remote sensing images and field investigations. Gradually declining MI indicated that climate change was not the major cause of aeolian desertification development during the last 40 years, while increasing population should be the underlying cause of local aeolian desertification. Irrational human activities mainly including unsuitable reclamation in the 1960s and lasting over-grazing after 1980 are direct causes contributing to local aeolian desertification, especially over-grazing, while climate change often played a revealer of irrational human activities mainly through drought events. Over-grazing and undesirable climate have different functions during the whole aeolian desertification process. Over-grazing gradually changed grasslands to slight aeolian desertified lands at the initial stage, while climate with windy days or droughts often accelerated formation of serious aeolian desertified lands. Aeolian desertification in the study area both possesses occurrence possibility and great rehabilitative potential. At present, more integrated countermeasures combating local aeolian desertification still are expected.

Keywords Aeolian desertification · Climate change · Human activities · Reclamation · Over-grazing · Otindag Sandy Land

Introduction

At present, aeolian desertification is one of the most serious environmental and socio-economic problems at global scales especially in arid, semi-arid and dry sub-humid areas of Africa, Central Asia, Australia and North China.

The Otindag Sandy Land is an important ecological barrier to block dust storms originated in the steppe of the Mongolian Plateau and the western China to be transported to Beijing. With aeolian desertification occurrence at the end of 1950s (Chen et al. 1960; Yang 1964), however, rehabilitation mainly occurred at that time (Zhu et al. 1981; Zhu 1999), which compared to that rapid aeolian desertification over recent years in this region (e.g., Wulantuya et al. 2001; Liu and Wang 2004a). In addition, frequent dust-storms in the end of 1990s were considered to be relevant with rapid aeolian desertification occurrence in North China (Ye et al. 2000), and anthropogenic factors are the main contributors of aeolian desertification in this region (Li et al. 2002; Wu et al. 2003; Dong 2000). At present, the results are still unclear because researchers used different classifications to evaluate the degree of aeolian desertification in this region. Although significance of coupling and feedback mechanism in aeolian desertification development had been recognized (Charney 1975; Sun and Li 2002; Chang et al. 2005), and Zhu et al. (1981) had proposed that period of aeolian desertification occurrence often related to major history events which mostly accompanied with droughts; coupling and cumulative impacts were ignored in many cases. In fact, aeolian desertification is a complex process which co-worked by different factors. The increased awareness about threats of aeolian desertification, and willingness to combat it, requires better knowledge about its distinct causes in order to take the most efficient and sustainable actions. According to vegetation information, many works attempted to discriminate climate or human-induced degradation in Syria (Jason and Roland 2003) and Otindag Sandy Land (Zheng et al. 2006). Following results of previous studies (Wang et al. 2003; Xue et al. 2005; Liu and Wang 2004a), with proxies for human activities and variations in climatic indices, Wang et al. (2006) identified the relative role of climatic and human factors in aeolian desertification in semiarid China.

In this paper aeolian desertification situation in the Otindag Sandy Land over the past 30 years was explored, and the causes of aeolian desertification in this region were discussed.

Study area and aeolian desertification state in 2000

Otindag Sandy Land is located at the eastern Inner Mongolian Plateau, between 112°30′E to118°E and 41°30′N to 44°30′N with elevation between 1,100 and 1,400 m (Fig. 1), and is dominantly controlled by arid and semiarid continental climate. The rainfalls are 350–400 mm at the southeast and 100–200 mm at the northwest, and about 70% of annual rainfall events occur in June to August due to activity of southeast monsoon in this period. The annual evaporation is 2,000–2,700 mm; annual mean temperature 0–3°C, sunshine hours 3,000–3,200 h, and the frost-free season is about 100–110 days. There is high wind activity in winter and spring especially in April and May, annual mean wind velocity is 3.5–5.0 m s^{-1}, and number of windy days (instantaneous wind speed exceed 17.2 m s^{-1} within a day) is 50–80 days in this region. Many lakes scatter in the Otindag Sandy Land. In the middle and eastern parts of Sandy Land, elms grow on the surface of fixed and semi-fixed dunes, and grasses cover most interdunes, compared to that the west is occupied by semi-fixed and few mobile dunes. Aeolian soils with different steppe characteristics are developed in this region, and usually in the eastern Sandy Land 4–6 and 3–5 layers of sands and dark brown paleosols can be easily found in dune profiles. The grain sizes of sands are about 1–4∅, which are easily to be eroded by wind. Traditionally the northern Otindag Sandy Land was used as rangelands and the southern such as Duolun County, Taipusi Qi and the south of Zhenglan Qi was reclaimed for rain-fed croplands. Vegetation cover just is low in dry and windy seasons, as resulted in wind erosion occurrence and aeolian desertified lands expanding once land surface was disturbed by human activities.

Aeolian desertified lands are up to 40,766.85 km^2 in 2000, which occupied 27.04% of total areas of Otindag Sandy Land. Areas of aeolian desertified lands in Zhenglan Qi and Zhengxiangbai Qi both exceeded half of its administrative area (Liu et al. 2004a). Four aeolian desertification types (Chen 1991) can be classified in the study area: surface of grasslands in northern Sonid Zuoqi and Sonid Youqi were eroded by winds and were accumulated by coarse sands (Fig. 2g); reactivation of fixed dunes and shifting dunes in patches were changed into stripe or sheet ones in the middle Zhenglan Qi, Zhengxiangbai Qi, Hexigten Qi, as well as the south part of Abaga Qi and Xilinhot City (Fig. 2a–e); farmlands in the south suffered from soil erosion by wind (Fig. 2i); and many shrub-coppice dunes and wind-eroded badlands were developed in the region (Fig. 2f, h).

Materials and methods

Aeolian desertification information in the 1950s was obtained from aerial photos in the late 1950s and previous studies (Chen et al. 1960; Yang 1964). Data obtained from the false color composites made up of bands 4, 3, 2 (R, G, B) of Landsat 5 Thematic Mapper (TM) images in September 1987, 2000 and 2005 and Landsat

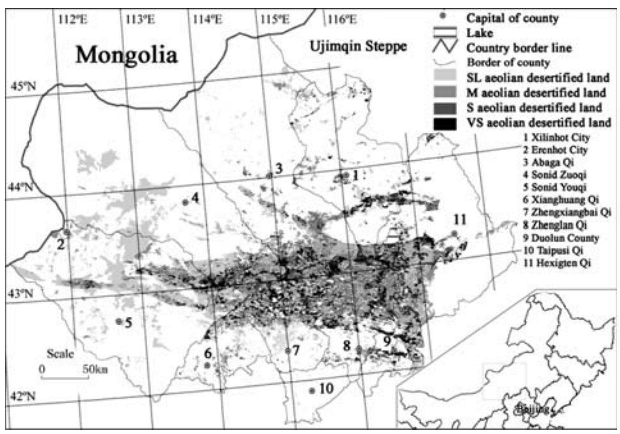

Fig. 1 Location of Otindag Sandy Land and distribution of aeolian desertified lands

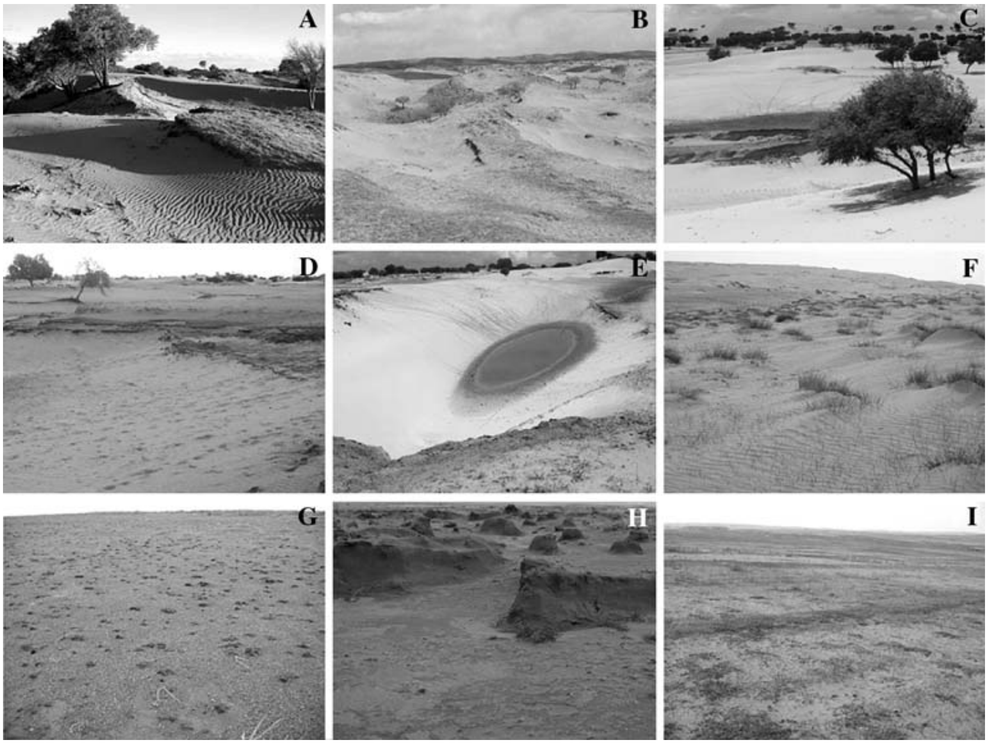

Fig. 2 Main types of aeolian desertified lands in Otindag Sandy Land (**a**–**e** Reactivation of fixed and semi-fixed dunes; **f** Coppice dunes in leeward; **g** Bare coarse surface eroded by strong wind; **h** Wind-eroded badlands; **i** Abandoned farmland due to aeolian desertification)

MSS image in 1977 was used as primary information. And Zhenglan Qi located at the center of Otindag Sandy Land (a typical county-level administrative area in Inner Mongolia) was selected for detailed analysis on aeolian desertification process from 1977 to 2005, where reactivation of fixed and semi-fixed dunes is main aeolian desertification processes. Spatial resolution of the TM images is 30×30 m, and MSS images 60×60 m. The images were corrected by using the Erdas Imagine provided by ERDAS. Reference to 1/50,000 topographic maps and lots of digital photos by camera with accurate GPS data during field investigation, remote sensing images were interpreted by adopting man–machine conversation method under ArcView 3.2 and ARC/INFO 8.0 software, according the same classification criteria (Table 1, Wu 2005). The investigation was conducted continually from 2002 to 2006 in the study area, and local 104 farmers and herders were interviewed for cause analysis. From April to May respectively in 2004 and 2006 field experiments on soil erosion by wind on sand dunes with different levels of stability and marking were performed for assessing annual expansion area.

Because aeolian desertification evaluation not only includes the total aeolian desertified area, but also includes different severities of aeolian desertification, and very serious aeolian desertified lands were explored additionally.

In arid and semi-arid regions many (Nicholson et al. 1994; Li et al. 2000) indicated that NDVI is highly related with precipitation, including Otindag Sandy Land (He et al. 2003). But Chepil (1962) and FAO (1979) proposed a wind erosion climatic factor can reflect role of climate change in aeolian desertification better, which containing key erosion factors such as mean wind velocity, monthly mean rainfall and mean temperature or Potential Evapotranspiration. In addition, Tsoar (2005) argued that vegetated dunes be developed under condition of the wind power is sufficiently low. Lancaster (1988) proposed sand mobility index (M), although developed for dunes in desert environments, and it has been widely used to characterize dune activity in sub-humid to semi-arid environments (Jorgensen 1992; Wolfe 1997; David 2005). Considering soil wind erosion in the study area mainly occurring in spring (Liu et al.

Table 1 Classification and indicators of aeolian desertification degrees

Degree	Percent of blowns and area in total/%	Percent of annual expansion area/%	Percent of vegetation cover/%
L	< 5	< 1	> 60
M	5–25	1–2	60–30
S	25–50	2–5	30–10
VS	> 50	> 5	10–0

L, *M*, *S* and *VS* are the areas with slight, moderate, serious, and very serious aeolian desertification, respectively

Table 2 Aeolian desertification development in Zhenglan Qi over the last 30 years

Zhenglan Qi	1977 (km^2)	1987 (km^2)	2000 (km^2)	2005 (km^2)	Development rate in 1977–1987 (km^2 a^{-1})	Development rate in 1987–2000 (km^2 a^{-1})	Development rate in 2000–2005 (km^2 a^{-1})
SL	1,131.4	1,060.1	1,762.3	1,808.4	−7.13	+54.02	+9.22
M	1,683.4	1,103.2	2,005.6	1,977.4	−58.02	+69.42	−5.64
S	1,570.3	1,498.4	1,210.8	1,366.7	−7.19	−22.12	+31.18
VS	582.4	1,705.1	1,059.9	807.2	+112.27	−49.63	−50.54
Total	4,967.5	5,366.8	6,038.6	5,959.7	+39.93	+51.68	−15.78

+ for spread of aeolian desertified lands
− for rehabilitation of aeolian desertified lands

2004a), in this paper we choose and modify it to explore the roles of natural factors in aeolian desertification process of the study area:

$$MI = V_s \times PE \times R^{-1},$$

where MI is sand mobility index after modification; V_s is the mean wind velocity in spring (March–May); PE is the annual potential evaporation and R is the annual rainfall. In addition, multi-temporal VGT-S10 (10-day synthesis product) radiometric data for April 1, 1998 to December 31, 2004 were downloaded from the free VGT products website (http://www.free.vgt.vito.be), and annual maximum NDVI during 1998–2004 deriving from SPOT images with maximum value NDVI composite (MVC) method was used to explore relation between vegetation and drought. With availability of data and easy to operate, drought index (DI) was selected, the ratio between annual potential evaporation (PE) and annual rainfall (R). And numbers of livestock and areas of farmlands year by year are used to explore the roles of human activities in aeolian desertification processes in this study area.

Aeolian desertified lands in different periods, climate change and anthropogenic factors change were compared to analyze causes causing local aeolian desertification.

Results

Processes of aeolian desertification in the study area

The temporal and spatial distributions of aeolian desertified lands from the mid-1970s to 2005 in Zhenglan Qi were showed in Table 2 and Fig. 3.

Over the past 50 years aeolian desertification strongly occurred in Otindag Sandy Land (Fig. 4), and three periods are recognized: before 1987, rapid aeolian desertification occurred in this region, including slight, moderate, and very serious grades, and especially aeolian desertification with very serious grades developed with a rate of 112 km^2 a^{-1} during 1977–1987; from 1987 to 2000, rate of aeolian desertification decreased and part of shifting dunes rehabilitated, as is showed in Fig. 4; and from 2000 to 2005, rehabilitation occurred, whichever of total aeolian desertified lands or very serious aeolian desertified lands (Fig. 4). Before 2000, rate of aeolian desertification was 40–50 km^2 a^{-1} and only in recent years parts of aeolian desertified lands were rehabilitated and part lands with very serious aeolian desertification were changed into that with slight ones from 2000 to 2005.

In 1977, aeolian desertification with VS grades only occurred at few places and with smaller areas in the east and west of Sandy Land, but it strongly developed throughout the whole Sandy Land during 1977 to 1987 with an alarming rate. In 2000, lands with VS grades of aeolian desertification converged on an irregular belt (Fig. 3) and total areas occupied 59.3% of Zhenglan Qi. Although there was some rehabilitation occurrence from the early 2000s to present in this region, aeolian

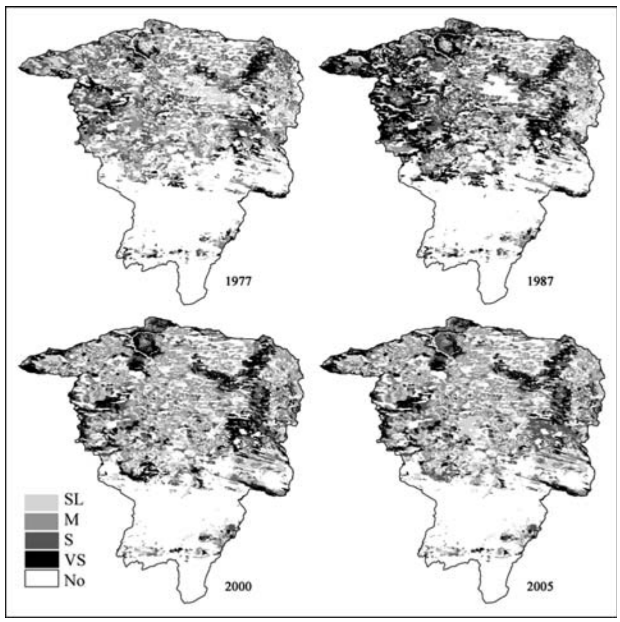

Fig. 3 Spatial distribution of various aeolian desertified lands in Zhenglan Qi over time

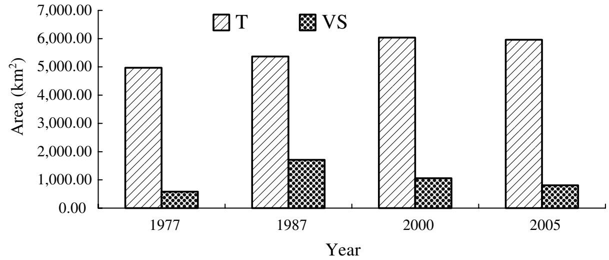

Fig. 4 Change of *T* and *VS* in Zhenglan Qi from the mid-1970s to 2005 (*T* is for total aeolian desertified lands; *VS* is for very serious aeolian desertified lands)

Table 3 Correlation between DI and NDVI in Zhenglan Qi in recent 7 years

Zhenglan Qi	1998	1999	2000	2001	2002	2003	2004
DI	0.178	0.147	0.232	0.208	0.174	0.137	0.146
Mean NDVI	0.266	0.274	−0.144	−0.035	0.008	0.195	0.147

desertification in 2005 was still very severe. Only parts of lands with VS grades of aeolian desertification in northwestern and southern typical area were changed into grasslands and woodlands, while other lighter aeolian desertified lands basically did not get melioration (Table 2, Fig. 3). Control of VS revealed that aeolian desertified lands in the study area possesses great rehabilitative potential, while unaltered L, M and S aeolian desertified lands prone to reverse at the same period revealed that aeolian desertification is a complex process.

Causes of desertification in the study area

Climate factors

Climate change trend contributing to reverse aeolian desertification Aeolian desertification occurrence mainly depends on association of wind and vegetation cover in areas with abundant sandy materials. Sun and Li (2002) proposed the combination of drought, high wind erosion, poor crop and large livestock is mostly prone to aeolian desertification.

Climate change is widely thought as one of aeolian desertification causes and even as final factor, especially droughts (El-baz 1983; Chen 1986). Although drought has important influence on vegetation in the study area (e.g., Li et al. 2000; Table 3), DI changed little during the last 40 years (Fig. 5), while MI which directly affects sand mobility obviously decreased in the same period (Fig. 5).

In addition, heavy snow disaster in 1977 reduced numbers of livestock to the minimum over the last 40 years in the study region, as is advantage to rehabilitation of aeolian desertification occurrence, regardless of economic loss. Therefore, climate change was not the driver factor of aeolian desertification in the study area during the last 40 years.

Drought events occurrence accelerating aeolian desertification process Although climate did not change toward dryer, drought events once occurred during the last 40 years, such as droughts before 1980, 1989, 1997 and 2001 (Fig. 5). The coupling of the droughts and frequent windy weathers in the 1970s directly resulted in wind erosion of farmlands and reactivation of part fixed or semi-fixed sand dunes. As a result, areas of aeolian desertified lands reached 5,367 km^2 in 1987, and the areas of very serious aeolian desertified lands reached the maximum of the past 50 years (Table 2, Fig. 4). Another drought event from 2000 to 2002 is a very representative case, when not only resulted in rapid aeolian desertification process but also induced frequent sand-storms (Wang et al. 2002).

Anthropogenic factors

Human activities contributing to aeolian desertification development Population size increases by four times from 1947 to 2002 and grasslands per household decreasing. Whichsoever trends of livestock and farmland in the other regions of Sandy Land are similar to that of the Zhenglan Qi (Fig. 6, Zheng et al. 2006). The extensive reclaims which implemented during the early 1960s, largely increased the areas of farmlands in 1960s to 1970s. The direct results of extensive reclaims in this region are the loss of high-grade grasslands, and pressure increases on the remained ones (Zheng et al. 2006). Unfortunately, during the early 1960s to 1977, areas of aeolian desertified lands up to about 4,968 km^2 and many farmlands and high grade grasslands experienced rapid aeolian desertification in 1977 (Table 2).

Herds choose settlements in the early 1980s, as enhanced humans' resistance to natural disasters especially snow damages (Begzsuren et al. 2004), but it caused prolong disturbances on adjacent grasslands. Because the nomadics are rangeland management practice that over the centuries has proved to be sustainable and suited to the ecosystem carrying capacity (MA 2005). Due to reform of using grasslands system and implementing Double Contract Policy (both livestocks and grasslands be managed by households) about Grassland and Livestock since 1982, livestock began to steadily increase again (Fig. 6) and grassland occupied by unit sheep rapidly declined (Liu et al. 2004b), and pressure from population and livestock exceed the limit of capacity (Han et al. 2002). Settlements of herdsmen and overgrazing resulted in wide aeolian desertification during this period. As a result, when parts of lands with VS grades of aeolian desertification were controlled and rehabilitated, while in more grasslands slight and moderate aeolian desertification occurred till 2000 (Table 2, Fig. 3).

Hahn et al. (2005) pointed that in semi-arid and arid areas livestock and vegetation are usually not at equilibrium because of highly variable climate conditions. High pressure on grasslands partly comes from decrease of grasslands area due to reclamation and aeolian desertification, and partly from livestock increases. Even if we taking the livestock sizes in 2002 as the baseline (because this number is a more reasonable carrying capacity after implementing grass-animals balance policy, though it still more than theoretical one), during the past 50 years there are 20 years including 1965, 1973–1976 and 1988–2002 overgrazing occurred. Overgrazing by domestic livestock has been widely accepted as an important cause of land degradation in rangelands (Tainton 1999; Zhao et al. 2005).

Besides, other economic activities such as mining, road building, traffic-off and recreation strongly destroyed grasslands. For example, only in Xilingol Meng vehicles from few ones in 1949 increased to 104 thousand in 2005, which is also a induce of desertification. Field investigation showed vehicles' destroy is very severe, as often caused linear-blowouts along roads with 10–40 m wide and 0.5–2 m deep.

In addition, investigations and interviews showed that more than 80% of local herdsmen support present policies (SBXM 2006), but another households still continue to hyperploid's grazing against local government. In fact, 82% of them also had known that overgrazing and other irrational human activities easily caused aeolian desertification, but they had no alterative means only for surviving. Thus, latent factors inducing aeolian desertification, for example income, still require further attentions and more sustainable management means.

Change trend of total aeolian desertified lands in Fig. 4 is obviously inconsistent with the MI (Fig. 5), while consistent with proxies of human activities such as population size, areas of farmlands and numbers of livestock. Field investigation and correlative analysis showed human activities (particularly over-grazing) mainly transformed grasslands to slight aeolian desertified lands and should be the main contributor to aeolian desertification occurrence. Another interesting thing, VS change had higher correlation with MI, as probably indicated climate acting as a revealer and magnifier especially in the last 20 years in the study area.

Protective management practices promoting aeolian desertification rehabilitation Frequency of dust storms increased in the early 2000s compelled humans to carry out many protective projects and countermeasures such as Enclosuring and Migrating Policy for combating aeolian desertification in this region. There were obvious increases for the mean NDVI in Zhenglan Qi since 2001 (Table 3), one is due to much rainfall, and the other hand is better management. Many field quadrat investigations also proved the rehabilitation potential of aeolian desertified lands is very huge.

Conclusions

Aeolian desertification processes in the study area have three stages: rapid occurrence before 1987, parts of rehabilitation and most of deterioration from 1987 to 2000 and part rapid rehabilitation occurrence from 2000 to 2005. Aeolian desertification in the study area not only possesses occurrence possibility, but also great rehabilitative potential.

Roles of climate change and human activities in aeolian desertification varied with time. In general, population size increase is the underlying cause of aeolian desertification. Irrational human activities such as extensive reclamation during the 1960s and steadily

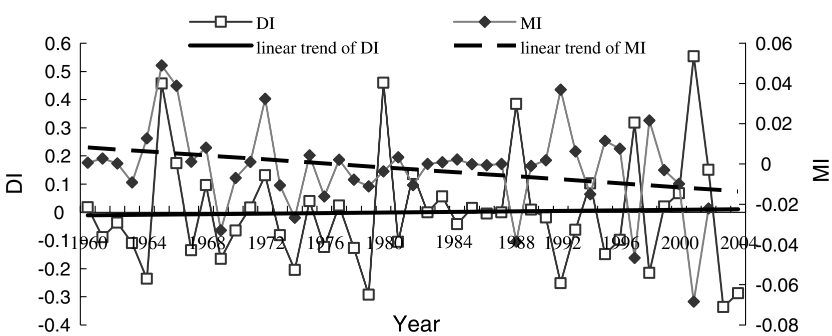

Fig. 5 Change of main climatic factors in Otindag Sandy Land over the last 40 years

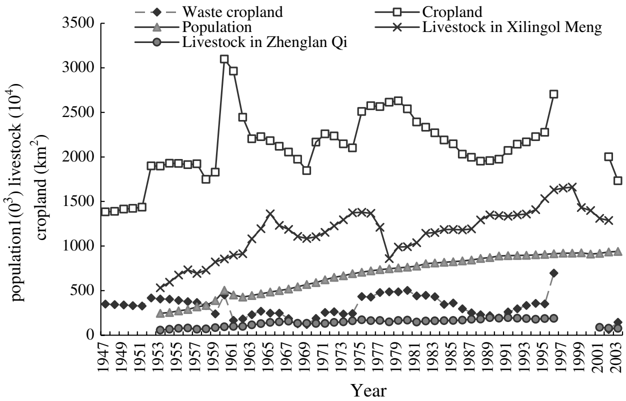

Fig. 6 Change of main anthropogenic factors in Otindag Sandy Land over the last 50 years

livestock increases and resulting over-grazing after 1978 should be responsible for aeolian desertification occurrence, while climatic change is not the main cause of desertification. Climate played the role of revealing irrational human activities through undesirable drought events.

Only depending on current protective methods such as fence building and livestock size decrease are difficult to avoid aeolian desertification. More sustainable management means are expected.

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