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RESEARCH ARTICLE

Driving mechanisms of the desertification process in the Horqin Sandy Land——A case study in Zhalute Banner, Inner Mongolia of China

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Abstract Both natural and human factors contributing to desertification were examined to understand the driving mechanisms of the desertification process in Zhalute Banner, Inner Mongolia of China. The coefficient of variation (*CV*) and climate departure index (*Z*) were calculated to examine the fluctuations and trends of interannual variations of temperature and precipitation; TM remote sensing data was extracted to obtain the sandy land area; linear regression analysis was used to analyze climate changes and the socio-economic evolution over the years, and it was also used to standardize the variables, which included annual temperature, annual precipitation, human population, and livestock number, in order to measure the difference in the rate of change between climate and anthropogenic factors. The results showed that there was a rise of about 1.6°C in temperature but no significant change in precipitation from 1961 to 2000, which indicated a short-term climatic trend toward aridity in this area, a condition necessary for desertification. The fraction of precipitation in spring tended to increase whilst the fraction in autumn and winter decreased. Both the human population and livestock population had tripled and the cultivated area had doubled from 1961 to 2000, suggesting that socio-economic factors might have contributed more significantly to the desertification. Between 1988 and 1997, the sandy land area increased by 12.5%, nearly 2.4 times in the farming section. It could be concluded that the driving mechanisms of the desertification processes in Zhalute banner are mainly the policy of cropland expansion and the rising populations of humans and their livestock, which has affected the land use pattern in the past decades.

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1 Introduction

Synergy of the fragile natural environment and intensive human activities has been promoting progressive desertification in arid and semiarid northern China. Horqin Sandy Land, the largest area of sandy land in China [1], is one of the most severely desertified areas of China [2]. There have been many studies focusing on this area, addressing the climate variations, patterns of inward human migration, and land reclamation history of this area [3–6]. The major conclusions were as follows: First, the Horqin desert was formed at the end of the Upper Pleistocene epoch and at beginning of the Holocene epoch, and now it is in an intensely active period as a result of the unreasonable activities of human beings. Second, over-reclamation has been done for four times without proper protection measures, and has been the main factor causing desertification over the past fifty years, increasing the cultivated land while reducing the grassland. Third, high-resolution pollen records from Mali Bog support the theory that human settlement and agricultural and pastoral activities are the main factors enhancing the process of desertification.

Fourth, the climatic changes had great impact on the shift in the farming-pastoral transitional zone, which could then have acted as a trigger for desertification. Considering the multi-dimensional genesis of the desertification problem, both natural and human factors contributing to land degradation should be thoroughly examined to understand the driving mechanisms, especially those at a local scale. However, most of the previous studies did not cover all these factors. In this paper, Zhalute Banner of Inner Mongolia Autonomous Region located in the Horqin Sandy Land was focused on to examine the mechanisms contributing to accelerated land degradation and to assess the impact of rising temperatures on evapo-transpiration and consequent soil water status in the light of changing land use and population pressure from both humans and their livestock.

2 Materials and methods

2.1 Study area

Zhalute Banner (county) of Inner Mongolia Autonomous Region is located at 119° 13′ 48″–121° 56′ 5″ E, 43° 50′ 13″–45° 35′ 31″ N. It lies in the farming-pastoral transitional zone from the Northeast Plain to the Inner Mongolia Plateau (Fig. 1). The altitude is about 1400 m in its northwest part and declines to about 180 m in its southeast part. Its total area is about 17840 km^2. This county has a population of more than 300000, about 20% of which live in towns. The mean annual temperature is 6.4°C and mean annual precipitation is 378 mm, most of which occurs during June to August (Fig. 2).

2.2 Data resources and analysis

The meteorological data as well as the relevant socio-economic data was collected from Zhalute Banner, including temperature and precipitation for every 10-day period from 1961 to 2000, and the human population, animal population, and farmland area from 1947 to 1998 [7]. The meteorological data came from the official basal meteorological station, which is located at 120° 54′ E and 44° 34′ N, at an elevation of 265 m, about 1 km from Zhalute town and surrounded by grassland. The data on the desertified land area of Zhalute Banner in 1988 and 1997 used here were derived from Kang et al. [8], which were estimated based on Landsat-TM remote sensing images (121/29) on 26 June, 1988 and on 5 July, 1997, respectively.

The fluctuations and trends of the inter-annual variations of temperature and precipitation during the period from 1961–2000 were examined. The coefficient of variation (CV) and climate departure index (Z) were calculated as Eqs. (1) and (2):

$$CV = \frac{S}{\overline{X}} \times 100\% \quad (1)$$

where CV is the coefficient of variation; S is the standard

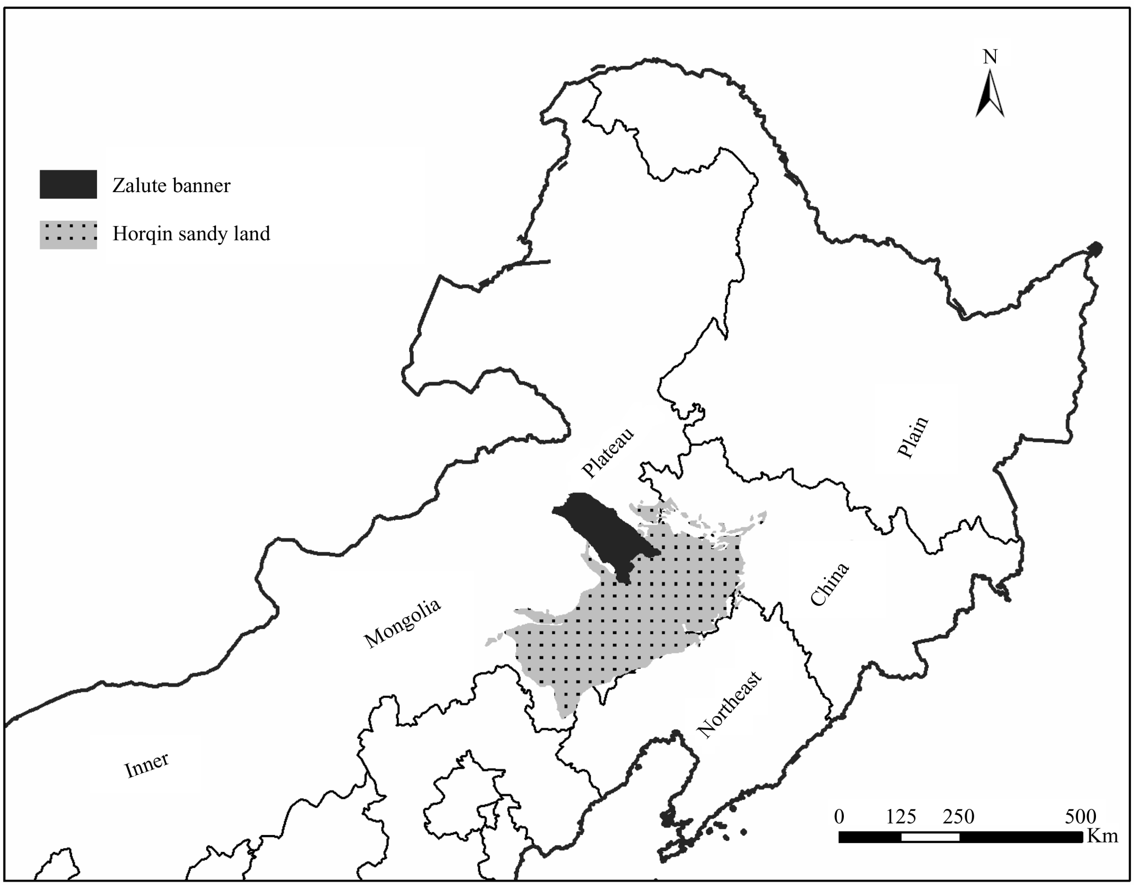

Fig. 1 Location of Zhalute Banner and Horqin Sandy Land, Inner Mongolia of China

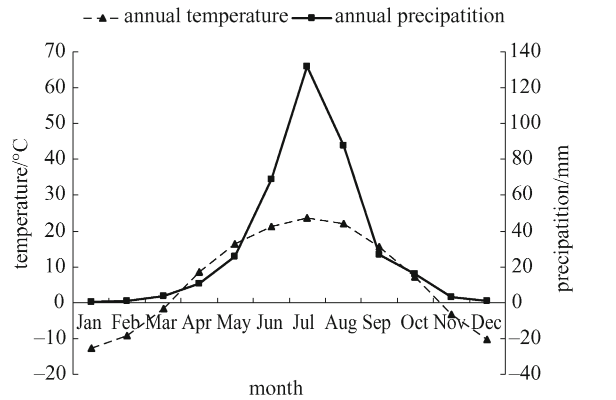

Fig. 2 Average temperature and precipitation of Zhalute, Inner Mongolia of China from 1961 to 2000

deviation; $\overline{X}$ is the mean of a given series.

$$Z = \frac{X - \overline{X}}{S} \tag{2}$$

where Z is the simple climate departure index; X is the temperature of each year; $\overline{X}$ is the mean of a given series; S is the standard deviation [9].

For each decade, the number of years that the Z values were beyond one standard deviation away from the mean was accumulated to show the variation in precipitation (percentage of years).

Linear regression analysis was used to analyze climate changes and the socio-economic evolution over the years and to standardize the variables in Eq. (3), including annual temperature, annual precipitation, human population, and livestock number, in order to measure the difference in the rate of change between climate and anthropogenic factors:

$$X_s = \frac{X - \overline{X}}{\overline{X}} \tag{3}$$

Another option used was socio-economic evolution, which was used to analyze changes in the three indices of population, livestock number, and farmland area, which are all related to desertification, and their relation with the increased sandy land area, local policies, and other factors.

3 Results

3.1 Climatic fluctuations

The mean annual temperature increased by 1.6°C from 1961 to 2000, which showed a statistically significant difference (Fig. 3). Although there was no statistically significant change in mean annual precipitation at the Zhalute station during this period (Fig. 4), the variation in precipitation showed increases from 22.2% in the 1960s and 20% in the 1970s to 50% in the 1980s and 63.6% in the 1990s (Fig. 5), respectively. Further, the estimated annual potential evapo-transpiration (PE) increased nearly 10%, whereas there was a decreasing trend in the P/PE ratio, which would undoubtedly increase climatic aridity; definitely, it would lead to a reduction in effective soil moisture, a condition necessary for desertification. The variation in precipitation in Zhalute Banner increased from the 1970s, from 20% to 63.6% (Fig. 2), making the natural ecosystem much more easily degraded under intensive human activities. In addition, the seasonal partition of precipitation had some apparent trends. From Table 1 it can be seen that the average annual precipitation in the 1970s was similar to that in 1990s, about 370 mm; whereas the spring fraction tended to increase nearly 3%, the fraction in autumn and winter tended to decrease.

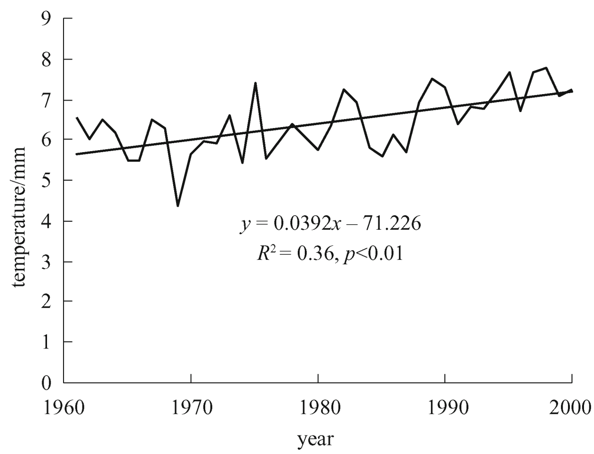

Fig. 3 Mean annual temperature in the town of Zhalute from 1960 to 2000
(The thin solid line denotes the mean annual temperature, the heavy solid line shows its linear trend.)

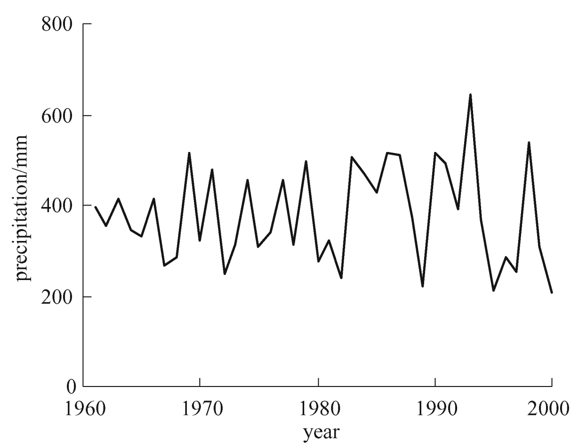

Fig. 4 Annual precipitation of Zhalute Banner from 1960 to 2000

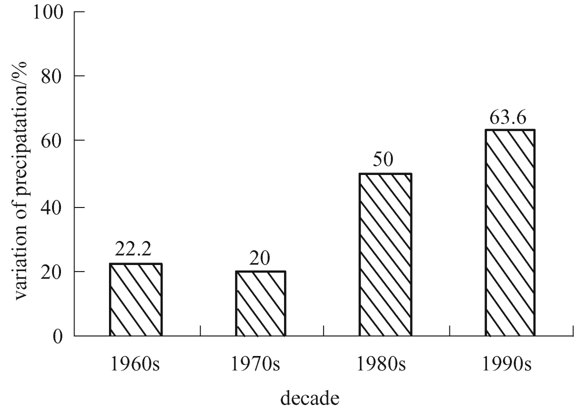

Fig. 5 Variation in precipitation in the past four decades of Zhalute Banner

Table 1 Seasonal partition of precipitation during the past four decades in Zhalute Banner, China

decades	in Spring/%	in Summer/%	in Autumn/%	in Winter/%	total/mm
1960's	9.43	77.43	12.43	0.71	363.68
1970's	8.95	76.74	13.24	1.07	368.23
1980's	10.9	75.25	13.18	0.66	409.24
1990's	12.89	76.52	9.97	0.62	369.46

3.2 Socio-economic evolution

The population, livestock number, and farmland area of Zhalute has been increasing ever since 1950. The population increased linearly from 3.8×10^4 in 1950 to 2.9×10^5 in 1997 (Fig. 6), while the population growth rate increased by a factor of 1.5 in the 1950s and decreased by 12% in the 1990s. The livestock number increased by 14 times as many from 1950 to 1997, characterized by several sharp rises followed by several sharp drops (Fig. 7). The total livestock number in 1997 reached 2.5 per hectare.

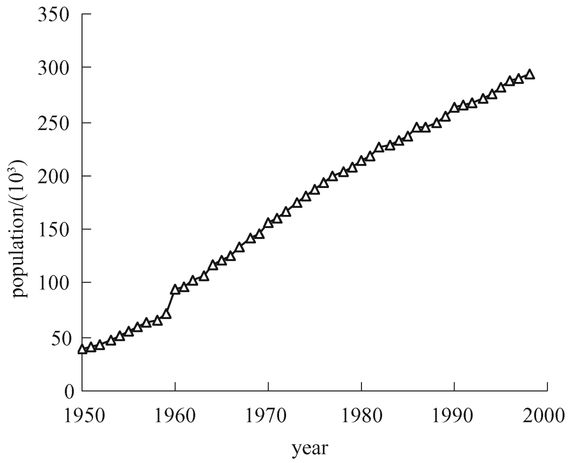

Fig. 6 Population of Zhalute Banner in the past fifty years

There were two leaps in the size of farmland area, occurring during two periods, from 1955 to 1964 and from 1988 to 1997, but no significant change was observed from 1964 to 1988 (Fig. 8). The farmland area quintupled from 1950 to 1997, and reached 139 200 hm^2 in 1997, which is 13.04% of the total land area of Zhalute Banner.

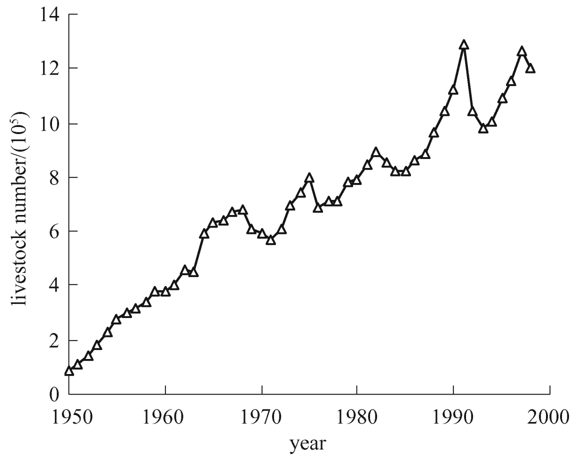

Fig. 7 Livestock number of Zhalute Banner in the past fifty years

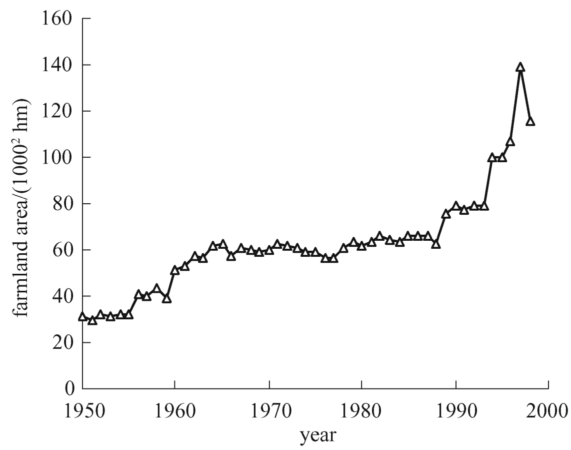

Fig. 8 Farmland area of Zhalute Banner in the past fifty years

The socio-economic conditions in Zhalute Banner developed at a much faster rate than did climate change. The rates of change of population and livestock number were four times faster than the rate of temperature increase(Fig. 9). To meet the food demands of the increased population, the need for more farmland in farm areas and more livestock in pastoral areas increased. However, Zhalute Banner, located in the central-Northern part of the Horqin Sand Land, mainly consists of foothills and sloping fields, limiting farmland expansion until the end of the 1980s. At that time, the policy of encouraging opening up of "wastelands" had begun, which indeed sped up the rate of increased cultivated land area without consideration for the soil quality and real land productivity. The figure further shows that the rate

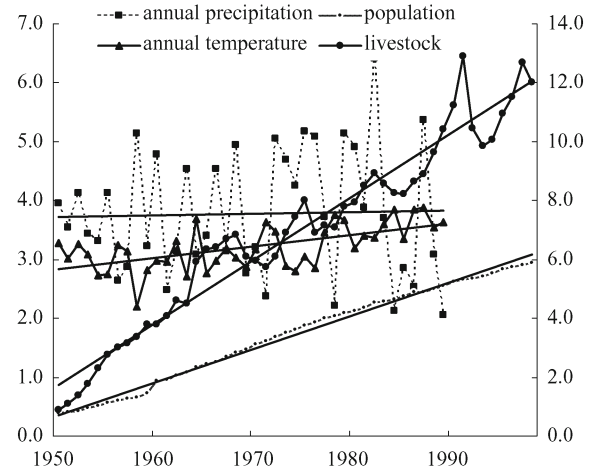

Fig. 9 Linear regression trends of annual temperature, annual precipitation, human population, and livestock number in Zhalute Banner
(The regression equations are as follows: $y = 0.0061x - 12.094$ for annual temperature, $R^2 = 0.36$, $p < 0.01$; $y = 0.0007x - 1.325$ for annual precipitation, $R^2 = 0.0008$, $p > 0.05$; $y = 0.0331x - 65.424$ for human population, $R^2 = 0.9919$, $p < 0.01$; $y = 0.0311x - 61.396$ for livestock number, $R^2 = 0.9444$, $p < 0.01$)

of increased farmland over the past fifty years was 61.3% in the 1950s, reaching its lowest in the 1970s at 2.2%, then began to gradually increase to 45.4% in the 1990s.

3.3 Sandy land area

The sandy land area was classified into three sections: farming, pastoral, and farming-pastoral, according to the proportion of agricultural and pastoral production and the proportion of the Han population and the Mongolian population [8]. The sandy land area in 1988 made up 1.8% of the total land area of Zhalute Banner, 9.2% of which was observed in the farming section, 72.1% in the pastoral section and 18.7% in the farming-pastoral section. In 1997, the sandy land area became three times bigger than that of 1988, accounting for 7% of the total land area. 21.7% of sandy land was seen in the farming section, 61.7% in the pastoral section and 16.6% in the farming-pastoral section (Fig. 10). Between 1988 and 1997, the process of desertification in the farming section accelerated, increasing to 12.5% of the total land area, nearly 2.4 times bigger during the decade, whilst the proportion of sandy land in the pastoral and farming-pastoral sections decreased by about 10% and 2%, respectively. Desertified farmland occupied 3871.28 km^2 in 1997 (up from 1641.28 km^2 only about 10 years earlier), largely due to unreasonable land reclamation driven by the policy factors mentioned above. Surely, this increase can primarily be attributed to human activities (including more population pressure and subsequent land use change) instead of climate change.

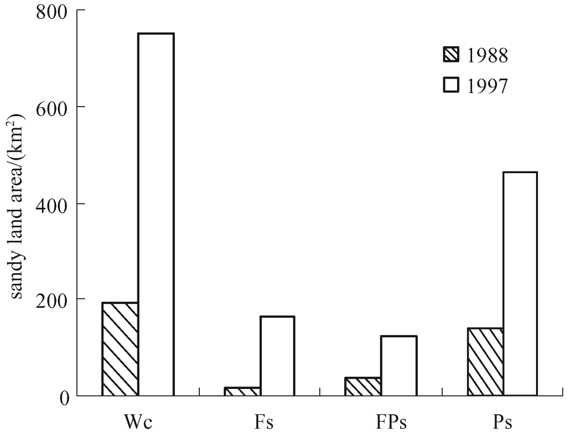

Fig. 10 Sandy land areas of Zhalute Banner in 1988 and 1997
Wc: whole county; Fs: farm section; FPs: farm-pastoral section; Ps: pastoral section

4 Discussion

Desertification is usually considered the consequence of the synergy of climatic change with intensified and irrational land use [10,11]. Most, if not all, of the researches have not pointed to simple answers about whether natural or human factors should be considered as the most important cause of current desertification. This study revealed a 1.6°C rise in the mean annual temperature in Zhalute from 1961 to 2000. Le Houérou et al. [12] estimated that every 1°C increase in temperature corresponded to an annual PET rise of approximately (5.25 ± 1.55) % from some 500 weather stations belonging to hyper-arid, arid, semi-arid, and dry sub-humid zones of 20 countries in Africa. The approximate statistical relationship between temperature and ETo is: $ETo \approx 77.5\ t +/- 2.3$, expressed in mm and °C, respectively, and ETo is estimated via the Penman-Monteith Equation [13]. The above Penman-Monteith Equation means that an increase of 1°C in annual temperature would correspond to 77.5 mm in annual ETo. Applying his method to Zhalute, the annual potential evapo-transpiration (PET) would increase nearly (8.4 ± 2.5)%. On the other hand, the P/PET ratio would decrease at the same rate since no significant change in annual precipitation took place in this area (Fig. 4), which would thus lead to an increase in the climatic aridity, definitely leading to a reduction in effective soil moisture, a condition necessary for desertification. The consequence of climatic fluctuation, especially the effect of the variation in the seasonal partition precipitation on desertification still needs to be further examined.

On the other hand, the natural vegetation is well adapted to its climate, and it is human influence that makes the land system more vulnerable to climatic variability [14]. In fact, the rate of climate change in Zhalute Banner was far less than that among human and livestock populations (Fig. 9). Luk [15] suggested that climatic fluctuations do not always lead to desertification, and a simple cause-and-effect relationship does not exist. Human settlement and agricultural and pastoral activities were suggested as the main factors enhancing the process of desertification in the Horqin Sandy Land based on archaeological relics and documentary records [3], a theory which was also proven by analysing the driving mechanisms of the desertification process in Zhalute Banner in this paper. Further, during the 1980s and in the early 1990s, policies and traditional norms (such as viewing the amount of livestock on hand as a symbol of wealth) were more crucial for the occurrence of desertification, as compared to population increase. Old grazing systems and some traditional concepts should be changed to concepts of modern animal husbandry, friendliness to the environment, and sustainability in land use patterns.

The society and economy of Zhalute Banner has experienced drastic changes over the past 50 years. Several immigrants and settlements from the Han population have rushed to this area since the early 20th century; in addition, the policy encouraging procreation caused a population explosion [16]. The people settled at a fixed place all these years due to population stresses, and abandoned the traditional nomadic life that Mongolian people had stuck to for more than a thousand years. Many villages and towns were established or expanded to hold the increasing population. Most of the people and livestock lived on the reclaimed land; however, the land was not able to support intensive utilization because of the fragile eco-environment in the semi-arid area, with erratic rainfall and sandy soil. Cropping practices in arid and semi-arid areas usually expose bare soils to wind erosion throughout much of the year and land is left barren after several years of cropping. To cultivate one hectare of farmland would cause desertification of an area three hectares big; therefore, cultivation was considered as the worst thing that happened to Mongolian grassland, and was blamed as the main cause of desertification in Inner Mongolia [17,18]. The farmland area expanded rapidly from 1988 to 1997 and coexisted with the increase of the desertified land area in Zhalute Banner. The expansion rate of desertification in the farming section of Zhalute was the fastest [8]. Mechanically, human-induced disturbance to the soil, including extensive farming and overgrazing could make the land susceptible to desertification. Desertification could reduce land productivity and household incomes and further weaken the local economy, which could finally restrict urbanization. On the other hand, the successful cases of desertification control programs in some local areas, such as those doing natural conservation and rangeland enclosure to exclude human destruction, indicates that human activities could be an important factor promoting desertification [19,20].

The determination of the responsibility of human activities in causing desertification would justify the endeavor to combat desertification. Unfortunately, the lack of desertified land area data in time series limits further quantitative analysis on the effects of socio-economic factors on land desertification. Nevertheless, no additional scientific studies are required before taking action to restrain human activities which induce desertification.

Zhalute Banner is an underdeveloped county in China. Agriculture is now the mainstay of the economy of Zhalute Banner. The livelihood of the native people prior to the 1950s largely depended upon herding, and this was threatened by reckless land conversion (and subsequent land abandonment) to cater to the inward migration of Han farmers—thus promoting desertification. The population increased six-fold during 1950–2000, and most of the population increase was due to immigrants from the other provinces. Yet the driving force for this population rush was not urbanization but famine. They moved to Zhalute Banner, settled in the countryside, and lived on grazing and farming. This posed great stress to the native ecosystem. Desertification is both a cause and a result of underdevelopment. Both urbanization and industrialization progress very slowly in Zhalute Banner. There is a vicious circle between desertification and urbanization and the situation can only get worse if the present trend toward increasing aridity brought on by rising temperatures and greater evapo-transpiration continues.

5 Conclusions

As is well known, desertification is a biophysical process which includes climate, vegetation, and soil. It can also be driven by socio-economic and political factors. From our case study in Zhalute Banner, several conclusions can be given as follows:

(1) In the past forty years, the rise in annual temperature, about 1.6°C, was significant but there was no significant rise in precipitation. The inter-annual variation of precipitation increased, and its seasonal partition had apparent trends: the spring fraction tended to increase by nearly 3%, and the fraction in autumn and winter tended to decrease; the decrease in the P/PE ratio increased climatic aridity in the Horqin sandy land.

(2) Most of the sandy land was seen in the pastoral area, however the speed of desertification was much higher in the farming area.

(3) In the past fifty years, the population has increased nearly 7.6 times, and the livestock number has increased 14 times, while farmland has quintupled.

It could be concluded that the driving mechanisms of the desertification process in Zhalute Banner are mainly the policies of cropland expansion and rising populations of humans and their livestock, which then affected the land use pattern in the past decades. With this background, climatic aridity provided a vulnerable environment for easy desertification; the optimal eco-economic paradigm, such as yard-breed-animal husbandry and rational policies, were found to be the two strong regulators which could guide local residents' activities.

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