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Spatio-temporal Variation of Wind Erosion in Inner Mongolia of China Between 2001 and 2010

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Abstract: Using Geographic Information System (GIS), based on wind speed, precipitation, topographic, soil, vegetation coverage and land use data of Inner Mongolia between 2001 and 2010, we applied the revised wind erosion equation (RWEQ) model to simulate wind erosion intensity. The results showed that an area of approximately 47.8×10^4 km^2 experienced wind erosion in 2010, 23.2% of this erosion could be rated as severe, and 46.0% as moderate. Both the area and the intensity of wind erosion had decreased from 2001 to 2010, the wind erosion area reduced 10.1%, and wind erosion intensity decreased by 29.4%. Precipitation, wind speed, population size and urbanization in rural areas, and gross domestic product of primary industry (GDP1) were the main factors influencing wind erosion. Overall, these factors accounted for 88.8% of the wind erosion. These results indicated that the decrease in wind erosion over the past decade related to the increase in precipitation and the decrease in the number of windy days, while modest urban development and optimization of the economic structure might partially reduced the level of ecological pressure, highlighting the importance of human activities in controlling wind erosion.

Keywords: wind erosion; revised wind erosion equation (RWEQ); driving factor

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1 Introduction

Wind erosion is one of the most serious environmental problems in arid and semiarid regions of the world (Buschiazzo and Zobeck, 2008). Wind erosion can lead to desertification (Lal, 1998; Callot *et al*., 2000), and is known to be responsible for the decrease in productivity often reported from arable soils due to loss of organic matter (Pimentel and Kounang, 1998). Wind erosion can also cause other major environmental problems, such as sand storms and episodes of reduced air quality (Hoffmann *et al*., 2011), which in turn can affect human health due to harmful effects of dust particles on the respiratory system (Copeland *et al*., 2009; De Longueville *et al*., 2009).

Wind erosion is a complex physical process, and represents one of the most important exogenetic forces generating and shaping a range of geological features. Different climate factors, such as wind speed, precipitation, and temperature and human activities including farming, pasturage, wood cutting, and digging can influence the effects of wind erosion over the landscape. Thus, changes in wind erosion patterns due to climate causes are temporary, while high levels of human impact associated with poor management strategies can accelerate wind erosion processes, potentially leading to

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environmental catastrophes and endanger human life andhealth, and agricultural production (Hu *et al*., 2003).

Woodruff and Siddoway (1965) proposed the wind erosion equation (WEQ), which came to be the most comprehensive and widely used model for estimating soil loss by wind from agricultural fields. However, the WEQ presented a series of limitations as empirical model. There revised wind erosion equation (RWEQ) combines empirical and modelling aspects, and represents the first wind erosion model that has been extensively tested under field conditions within and outside the Great Plains.

Inner Mongolia is located in the northeast of China. It includes areas of typical arid and semiarid climates and it is characterized by high levels of evaporation, low rainfall, and strong winds during spring.The region includes large extensions of desert environments, including the Gobi desert, which is particularly vulnerable to wind erosion. According to the latest Bulletin of National Soil and Water Conservation in China, nearly half area of Inner Mongolia is affected by wind erosion. Meanwhile, with the development of the economy and increasing population over the past years, human activities have caused profound disturbances to the natural environment and intensify the damage caused by wind erosion. Human practices such as excessive clearance of native vegetation, over grazing and inadequate agricultural practices have resulted in increased frequency and intensity of wind erosion in some regions (Shao, 2008), which can ultimately threaten the sustainable development of these regions.

Previous studies have studied wind erosion in different methods. On the one hand, mainly method in wind erosion studies of arid areas are qualitative analyses (Li, 2000; Zhang *et al*., 2001; Karssenberg and De Jong, 2005; Shi *et al*., 2009; Yang *et al*., 2010; Juan, 2012); on the other hand, wind tunnel experiments, ^{137}Cs tests, and wind erosion models have been used to estimate wind erosion intensity (Yan and Dong, 2003; Van Pelt *et al*., 2004; Liu *et al*., 2006; Daniel *et al*., 2007; Liu *et al*., 2007; Buschiazzo, 2008), however, wind erosion models applied to estimate wind erosion are still scarce in domestic.

Here, we analysed GIS data using the RWEQ (Bondy *et al*., 1980; Cole *et al*., 1983; Comis and Gerrietts, 1994; Fryrear *et al*., 1998) to determine average annual soil loss intensity and distribution patterns between 2001 and 2010 in Inner Mongolia, to assess spatiotemporal variations and factors influencing wind erosion. Thus, this study provides a reference for future management strategies aimed to control and reduce the effect of wind erosion, and to ensure social and economic sustainable development of the region.

2 Materials and Methods

2.1 Study area

The Inner Mongolia Autonomous Region (37°24'–53°23'N, 97°12'–126°04'E) is situated on the Mongolian Plateau in the northern China, with a total area approximately 1.183×10^6 km^2 and presents a typical continental monsoon climate, with an average annual precipitation of 50–450 mm, and average annual temperature of 0–8℃. From east to west, the main bioclimatic zones vary from humid, sub-humid, semi-arid, toarid, and extreme arid zones from east to west. This geographically variable environment is partially responsible for the abundance of natural resources of the region. Soil types also vary at the geographical scale, including black, dark brown, brown, and sierozem soil and grey-brown desert soil in that order if observed from east to west (Wang *et al*., 2012).

Land use varies across the region. East Inner Mongolia is characterized by the presence of large extension of forests, while grassland dominates in the central parts, desert in the west, pasture land in the north, and farmland in the south. Inner Mongolia is one of the areas with serious wind erosion problem and drastic land use change in China. This region has been dramatically influenced by policies supporting food production while neglecting grassland conservation, transforming grasslands to arable at large scales, leading to grassland desertification approximately 1.00×10^6 ha (Miao, 1996). Thus, overexploitation of grasslands has become a serious environmental issue. The results of previous studies showed that the rate of overexploitation of grasslands in the region increased from 23.6% in 1986 to 56.7% in 1992 (Xu and Bai, 1997), mainly driven by the population growth experienced in the region between 1980 and 1990, leading to grassland degradation and desertification. Some areas even become unlivable, such as eastern and western Suninte, and Siziwang districts, where surface soil had lost the protection of natural vegetation and enhancing wind erosion. Between 1993 and 2000, over 20 sandstorms a year were recorded from middle and west Inner Mongolia. In general, wind erosion rate increased rapidly within this period, severely affecting normal life and agricultural production in Inner Mongolia (Jiang, 1988; Li, 1997; Chen, 2000; Li *et al.*, 2001; Li *et al.*, 2011) (Fig. 1).

2.2 Model and analyses

2.2.1 Revised wind erosion equation model

The RWEQ model estimates soil loss for a certain location (S_L). Firstly, weather, soil erodible, soil crust, surface roughness and vegetation cover factors are used to calculate the maximum transported capacity by wind (Q_{max}) and the critical field length (S) as follows (Fryrear, 1998):

$$Q_{max} = 109.8(WF \times EF \times SCF \times K' \times C) \tag{1}$$

$$S = 150.71(WF \times EF \times SCF \times K' \times C)^{-0.3711} \tag{2}$$

$$S_L = \frac{2 \cdot z}{S^2} Q_{max} \cdot e^{-(z/s)^2} \tag{3}$$

where Q_{max} (kg/m) is the maximum transport capacity, S (m) is the critical field length (defined as the distance at which 63% of the maximum transport capacity is reached), S_L (kg/m^2) is the rate of soil loss caused by wind erosion, z (m) is the distance from the upwind edge of the field, WF is a weather factor, SCF represents soil crusting, EF is the soil erodible factor, C is the vegetation factor, and K' represents surface roughness.

Weather factor (*WF*). Wind is the basic driving force in RWEQ, whilst soil moisture and snow cover are important factors influencing wind erosion. The weather factor represents the influence of climatic condition on wind erosion, and combines wind speed, soil moisture, and snow cover as follows:

$$WF = Wf \times \frac{\rho}{\mathrm{g}} \times SW \times SD \tag{4}$$

where WF is the weather factor (kg/m), Wf is the wind factor (m^3/s^3), ρ is air density (kg/m^3), g is the acceleration due to gravity (m/s^2), SW is soil moisture, and SD represents snow cover.

Soil erodible factor (*EF*). The erodible fraction is that fraction of the surface 25 mm of soil that is lower than 0.84 mm in diameter as determined by a standard compact rotary sieve (Chepil, 1962). From a soil sieving

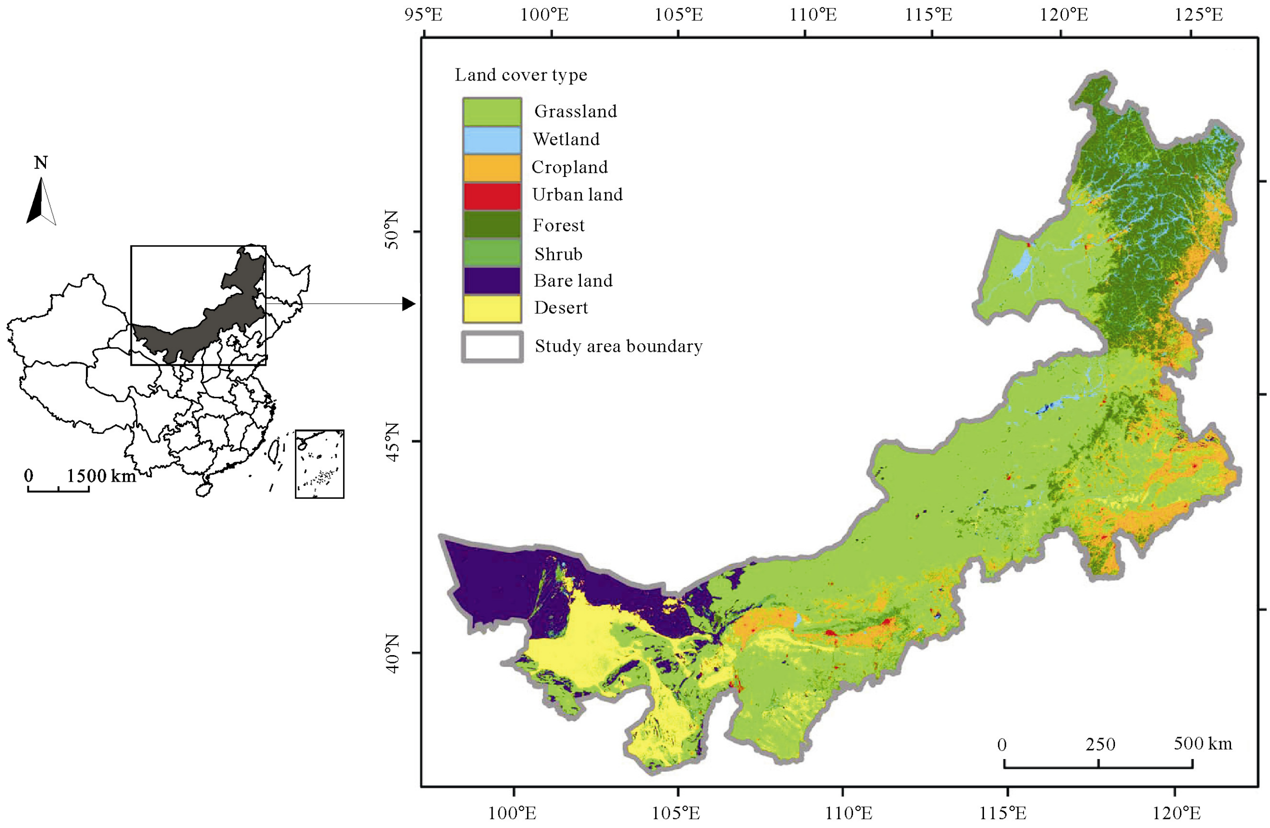

Fig. 1 Map of study area and ecosystem distribution

data base, the highest value for EF during a year for each site was correlated with basic soil physical and chemical properties (Fryear *et al.*, 1994). The developed formula is as follows.

$$EF = \frac{29.09 + 0.31Sa + 0.17Si + 0.33(Sa/cl) - 2.59OM - 0.95CaCO_3}{100} \tag{5}$$

where EF is the erodible factor, Sa is the sand content (%), Si is the silt content (%), cl is the caly content (%), OM is the organic matter (%), $CaCO_3$ is the calcium carbonate (%).

Soil Crusting Factor (SCF). When raindrops impact the soil surface, there is a redistribution of soil particles and a formation of surface crust. The resulting soil surface can be extremely hard or very fragile and may decrease or increase wind erosion potential (Zobeck, 1991). The SCF equation was developed using laboratory wind tunnel tests on resistance of soil aggregates and crusts to windblown sand (Hagen *et al.*, 1992).

$$SCF = \frac{1}{1 + 0.0066(cl)^2 + 0.021(OM)^2} \tag{6}$$

where SCF is the soil crusting factor, cl is the clay content (%), OM is the organic matter (%).

Vegetation Factor (C). The vegetation quantity on the soil surface has a significant impact on soil erosion by wind. To quantify the effect of vegetation, the fraction of the soil surface covered with nonerodible plant material (flat residues), the plant silhouette from standing plant residues (standing residues), and growing crop canopies (crop canopy) are used in RWEQ (Bilbro and Fryear, 1994). In this study, limited to available data, the flat residues of soil loss ratio coefficient (SLR_f) is calculated as a function of the soil that is covered with any type of vegetation.

$$SLR_\mathrm{f} = \mathrm{e}^{-0.0483(SC)} \tag{7}$$

where SLR_f is the vegetation factor, SC is the vegetation coverage (%).

Surface Roughness Factor (K'). Original RWEQ was designed to calculated wind erosion loss in a field scale. Tillage operations modify the soil surface roughness and flatten and bury crop residues (Nelson *et al.*, 1993). When scale up to a regional, roughness caused by topography will replace the soil ridge roughness, and calculated by Smith-Carson equation. The Smith-Carson equation and surface roughness factor (K') formula as follows (Li *et al.*, 2006):

$$K_\mathrm{r} = 0.2 \cdot \frac{(\Delta H)^2}{L} \tag{8}$$

$$K' = \mathrm{e}^{(1.86K_\mathrm{r} - 2.41K_\mathrm{r}^{0.934} - 0.127C\mathrm{rr})} \tag{9}$$

where, K_r is the topographic roughness length (cm), K' is the surface factor, ΔH is the elevation difference within the L distance, C_rr is the chain random roughness.

2.2.2 Statistical analysis

(1) Driving force analysis

Multiple factors influenced wind erosion, however, we could divided these factors into two categories: climate and human activity. In order to understand which factors are the most important leading changes in wind erosion patterns, we used redundancy analysis (RDA) (Jan *et al.*, 2003), constrained linear ordination method. Intensity and area of the study area affected by wind erosion were defined as response variables, and a total of 15 factors, temperature, precipitation, wind speed, number of windy days, rural population density, gross domestic product of three different industry (GDP1–3), urbanization level, number of grazing sheep, and farmland area, were included as explanatory variables, these factors were analysed to estimate their relative contribution to wind erosion using 999 Monte Carlo permutations, and all data were standardized before used.

(2) Wind erosion intensity trends

Simple linear regression analyses tool of ARCGIS were used to simulate trends inwind erosion intensity between 2001 and 2010 based on basic raster. The slope expression was estimated as (Mu *et al.*, 2012):

$$\theta = \frac{n \times \sum_{i=1}^{n} i \times C_i - \sum_{i=1}^{n} i \sum_{i=1}^{n} C_i}{n \times \sum_{i=1}^{n} i^2 - \left(\sum_{i=1}^{n} i\right)^2} \tag{10}$$

where θ is the trend slope, n is the total number of years, C_i represents wind erosion intensity in the ith year, with i set to 1–10. An area of $\theta < 0$ indicates a decrease in wind erosion intensity has decreased over the10-year period, while an area of $\theta > 0$ indicates an increase in wind erosion intensity over the10-year period studied.

2.2.3 Background data

We obtained daily precipitation, temperature, and wind speed data of Inner Mongolia for the period of 2001–2010 from the China Meteorological Data Sharing Service System (http://cdc.cma.gov.cn). Land use and vegetation cover data (2001–2010) were provided by the Institute of Remote Sensing and Digital Earth, Chinese Academy of Sciences. Soil properties, annual solar radiation data, and annual snow cover data were provided by the Cold and Arid Regions Sciences Data Center in Lanzhou (http://westdc.westgis.ac.cn). The Digital Elevation Model (90 m) was provided by the Computer Network Information Center, Chinese Academy of Sciences. Inner Mongolia socioeconomic development statistical data (2001–2010) were obtained from statistical yearbooks (IMARBS, 2001–2010).

2.2.4 Model calibration and validation

Different parameters were used to calculate soil loss driven by wind erosion using the RWEQ model. The results were divided into five categories according to the national industrial standard of Classification Standard of Soil Erosion (MWRPRC, 2008) as follows: slight erosion, moderate erosion, strong erosion, intense erosion, and severe erosion (Table 1).

Wind erosion intensities thus classified for the year 2000 were checked against the results of the China soil erosion investigation (for the year 2000) acquired from remote sensing data for qualitative verification. The results from both studies were highly consistent (R^2 = 0.89) despite using different approaches (Fig. 2), illustrating the viability of the RWEQ model to assess wind erosion intensity in Inner Mongolia.

3 Results

3.1 Temporal variability

Between 2001 and 2010, both areas exposed to wind (Fig. 3). erosion and intensity showed a clear decreasing trend. The area exposed to wind erosion decreased from 5.33×10^5 km^2 in 2001 to 4.78×10^5 km^2 in 2010, representing a reduction of 10.1%. The area exposed to wind erosion changed over the 10-year period, and 4.4×10^4 km^2 of the area changed to high wind intensity, representing to 7.9% of the area affected by wind erosion. On the other hand, 1.76×10^5 km^2 (33.1% the total area exposed to wind erosion) experienced a decrease from high to low wind intensity. Soil loss caused by wind erosion decreased 29.5% during the study period, from 5.70×10^9 t in 2001 to 4.02×10^9 t in 2010.

3.2 Spatial difference

The results showed a relatively high wind erosion rate in Inner Mongolia during the study period. Nearly half of the Inner Mongolia has experienced wind erosion, although most of the erosion occurred in the western Inner Mongolia (Fig. 4). The total wind erosion area was 4.78×10^5 km^2 in 2010, with 23.2% and 13.8% of the area experiencing severe and intense erosion, respectively, 8.9% of the area experienced strong erosion, and 20.0% and 34.0% moderate and slight erosion, respectively.

The 10-year trend for wind erosion intensity varied spatially. As shown in Fig. 5, the wind erosion intensity increased over an area of 1.12×10^5 km^2, mostly across the Alxa Plateau, and the west Inner Mongolia. The weakest levels of wind erosion intensities extended over 1.73×10^5 km^2, mostly distributed across the Erdos Plateau, west of the Hunshadake Sandy Land, and the Korqin Sandy Land.

The results of the spatial analysis showed an increase in wind erosion intensity from the east to west, with high intensity areas mainly distributed throughout the arid areas in the western Inner Mongolia. These areas

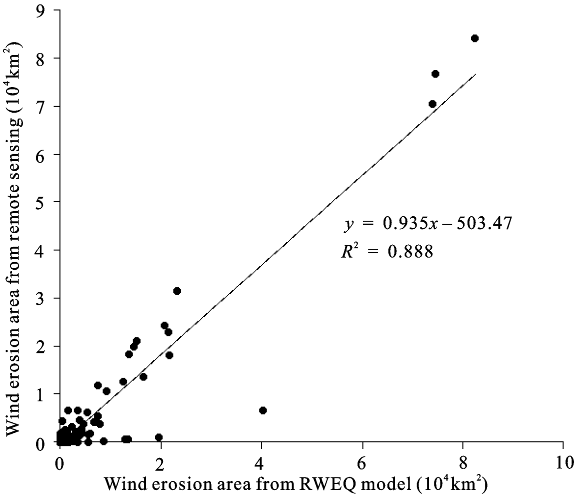

Fig. 2 Relationship between remote sensing data and revised wind erosion equation (RWEQ) results

Table 1 Wind erosion categories (t/(km^2·yr))

Erosion gradation	Slight erosion	Moderate erosion	Strong erosion	Intense erosion	Severe erosion
Erosion modulus	200–2500	2500–5000	5000–8000	8000–15000	> 15000

mainly present desert aeolian sandy soils and prairie aeolian sandy soils, which are highly vulnerable to wind erosion. Windy, drought conditions, and high temperature unfavorable for plant growth in this area, and soils lacking protection from overlaying vegetation cover become erodible. In general, the spatial distribution pattern of wind erosion was based on soil types, vegetation convert, and climate conditions.

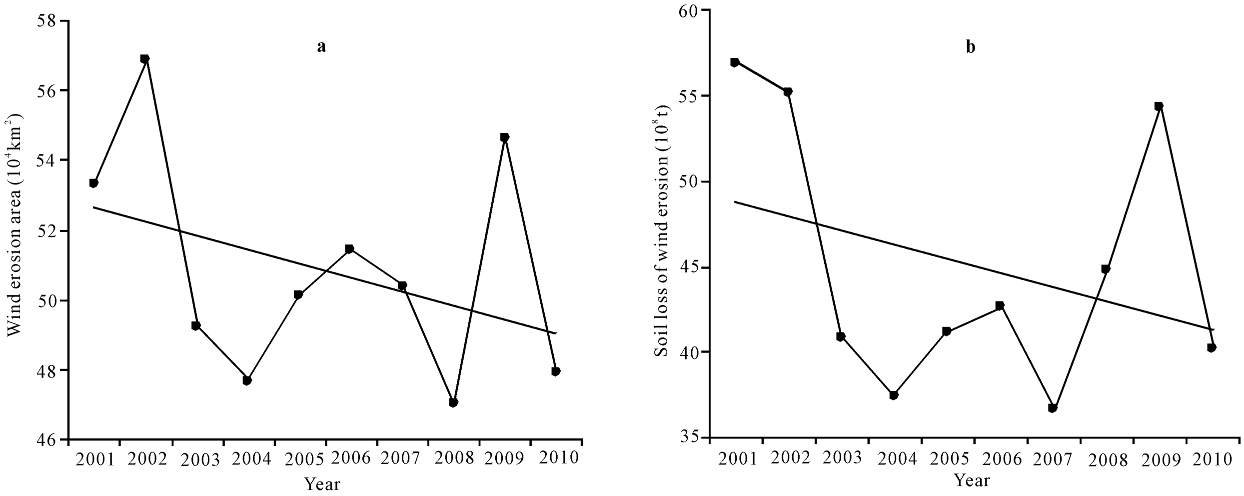

Fig. 3 Variation in soil loss and area affected by wind erosion in Inner Mongolia for period of 2000–2010. (a) wind erosion area; (b) soil loss of wind erosion

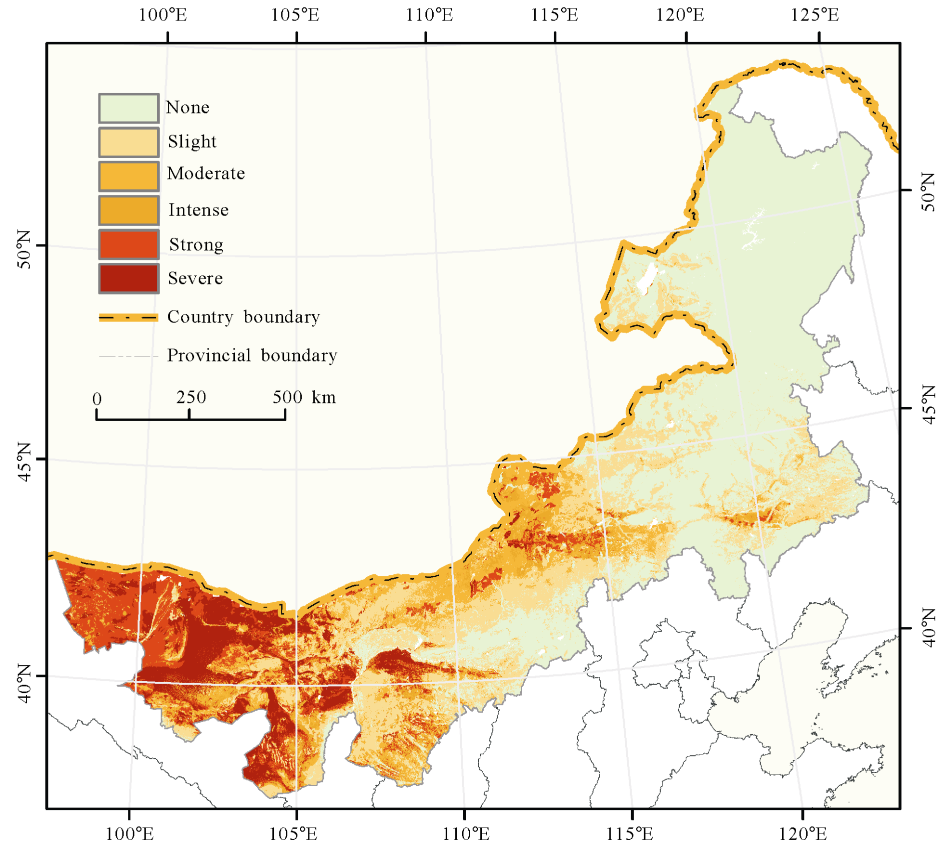

Fig. 4 Spatial pattern of wind erosion in Inner Mongolia

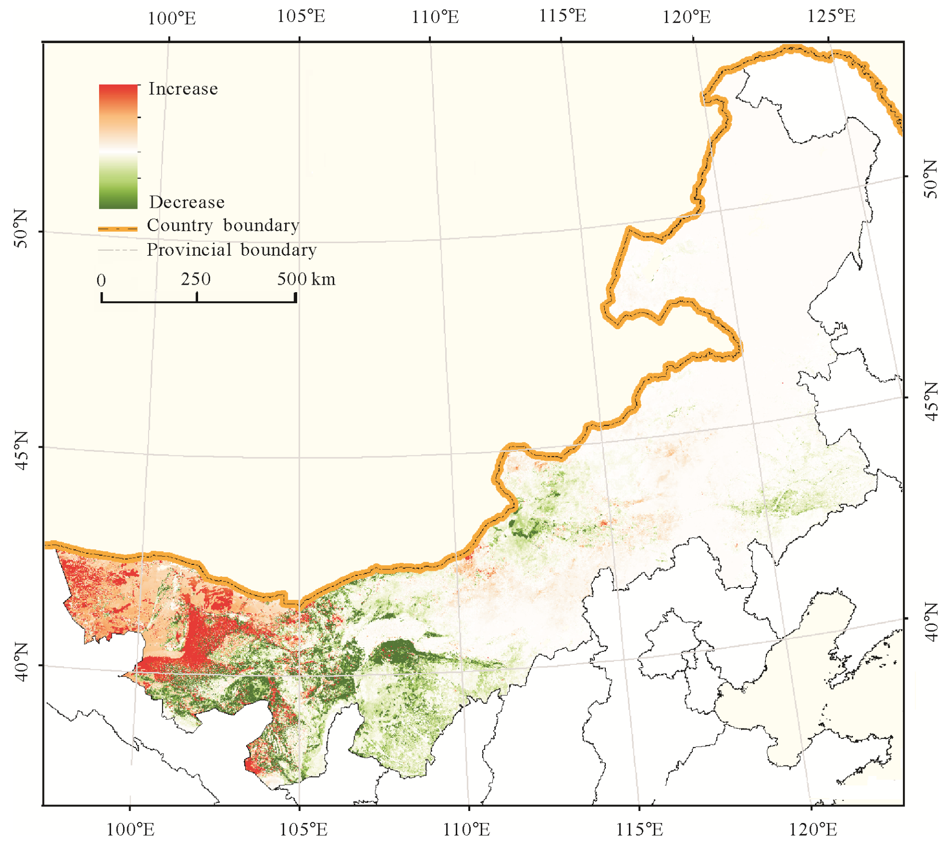

Fig. 5 Wind erosion intensity trends for period of 2000–2010

3.3 Driving force analysis

The RDA results showed that precipitation and wind were the main climate factors driving the decadal trend in wind erosion while rural population percent, urbanization level, and GDP1 rate were the main human activity factors. These factors combined explained 88.8% of the total variation in wind erosion measured during the study period (Fig. 6). Thus, the interaction of human and climate factors led to a decrease in wind erosion area and intensity in Inner Mongolia over the last decade. While climate was the main responsible for the change, human factors enhanced the variability observed.

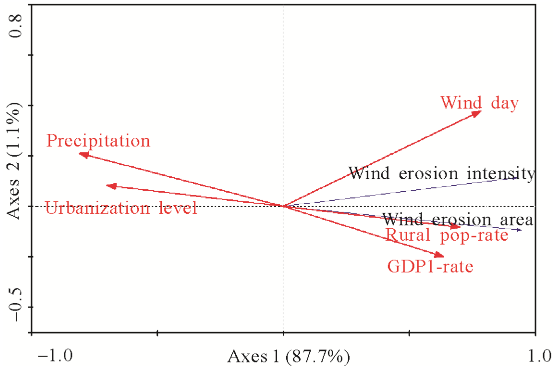

Fig. 6 Redundancy analysis (RDA) result about relationship between wind erosion change and driving facto. Rural pop-rate: the rate of rural population; GDP1-rate: the rate of GDP1

4 Discussion

4.1 Effect of precipitation on wind erosion

Climate change affects wind erosion slowly and gradually, mainly by influencing soil moisture, vegetation cover, and hydrological dynamics.From all influencing factors, precipitation is known to play an essential role (Su *et al.*, 2006). Our results showed a negative correlation between precipitation and wind erosion (Fig. 6). Overall precipitation can influence wind erosion considerably. For example, an increase in rainfall can directly lead to an increase in soil moisture, enhancing soil ability to withstand soil erosion. In addition, rainfall can stimulate plant growth, especially in arid and semi-arid areas, increasing vegetation cover and subsequently the level of protection against wind erosion. The level of precipitation fluctuated between 2001 and 2010, with a maximum precipitation of 366.9 mm measured in 2003 and a minimum precipitation of 234 mm measured in 2005, consistent with that, wind erosion area and intensity decreased between 2001 and 2005, and increased again between 2006 and 2010.

4.2 Effect of human activities on wind erosion

Human activity can significantly influence environmental development and evolution, representing a major driving factor. As a consequence of exponential population, the extension of land dedicated to agricultural production has increased rapidly, increasing human pressure over grasslands to meet agricultural demands. This change in land use has led to environmental degradation and reduced ecological productivity, accelerating desertification as a consequence of increased wind erosion (Liu and Ci, 1997). In the absence of targeted management and conservation strategies, human activities, including forest clearing, land use change of pasture land and vegetation clear-cutting, could potentially accelerate and aggravate wind erosion.

However, efficient management strategies and technological advances could help restricting and controlling detrimental activities, e.g., through afforestation, banning grazing, restoration of forests and grassland from farmlands, could potentially reverse the effects of wind erosion and prevent it (Su *et al*., 2006). Urbanization can increase rural-to-urban migration, reducing the pressure over the regional natural environment, improving production efficiency, and concentrating industry in hotspots enhancing pollution control. In addition, cities also present the advantage of prevent wind erosion. All of these factors are known to have a positive influence on sensitive arid and sub-arid regions (Chen, 2004; Hou *et al*., 2013).

Over the past decade, Inner Mongolia has experienced fast urbanization, and urban extension has increased from 42% in 2001 to 57% in 2010. By contrast, rural population decreased from 1.555×10^6 inhabitant in 2001 to 1.274×10^6 in 2010, representing a decrease in 15.2%, reflecting a clear urbanization tendency. During the same period, the GDP percent of primary industries has fallen by approximately 23%, indicating that economic activity has been transferred from agricultural and pastoral practices to industry and service sectors.

Agriculture and pastoral practices are sensitive to environmental degradation in fragile ecosystems. Thus, a decrease in human activity combined with efficient management strategies at the regional level at the appropriate temporal and spatial scale could expedite environmental recovery and help controlling wind erosion.

4.3 Remediation strategies to control wind erosion

Our results highlighted climate change as a major factor responsible for the decrease in wind erosion observed in Inner Mongolia between 2001 and 2010. In addition, human activity can also help reducing wind erosion, highlighting the need of targeted management strategies to direct human activity toward wind erosion control, including: 1) Accelerating industrial restructuring, reducing primary industrial production, restricting grassland cultivation, and limiting livestock population to prevent grassland degradation; 2) Enhancing environmental protection, accelerating natural vegetation growth and recovery by ensuring grassland and forest restoration from farmland and a timely recovery of degraded grassland, promoting rotational grazing of grassland, and placing livestock in corrals instead of allowing them to roam freely; 3) Improving production efficiency and reducing ecological pressure. To this end, we should increase the level of urbanization in a controlled way, and encourage population to concentrate in urban areas.

4.4 Limitation of RWEQ method

In this study, we applied the RWEQ model to assess wind erosion in Inner Mongolia between 2001 and 2010. Our results show high consistency with remote sensing data, indicating that the RWEQ model applied can be used to assess wind erosion in this region. However, China extends over a vast territory, with varying climate conditions, and large elevation differences. Thus, although this model was successfully validated for Inner Mongolia, further long-term experimental and monitoring data from other regions of China are required to validate the model for other areas. This validation should include a variety of geographical features and ecosystems and a careful revision of RWEQ parameters and equations to ensure the accuracy of the model. In addition, different vegetation types (grassland, shrub, forest, and farmland) present different resistances to wind erosion, which is not captured in the model. This aspect would also require further improvement in future work.

5 Conclusions

Our results show a reduction in wind erosion and soil loss in Inner Mongolia between 2001 and 2010. The area affected by wind erosion decreased by 10.1% during this period, while soil loss decreased by 29.5%. The area affected by wind erosion decreased from 5.33×10^5 km^2 in 2001 to 4.79×10^5 km^2 in 2010. Wind erosion intensity varied throughout the study period. To this end, and total area of 4.4×10^4 km^2 experienced an increase in wind erosion intensity from low to strong intensity, representing a 7.9% of the total area affected by wind erosion. On the other hand, 1.76×10^5 km^2 of the total area affected changed from strong to low intensity, representing 33.1% of the wind affected area. Wind erosion driven soil loss decreased from 5.70×10^9 t in 2001 to 4.02×10^9 t in 2010.

Wind erosion intensity varied at the spatial scale; wind erosion intensity and area affected increased from the east to west. High intensity areas were mainly distributed on arid areas in the western Inner Mongolia. In general, this spatial distribution pattern was consistent with the distribution patterns of erodible soil, vegetation cover, and precipitation in Inner Mongolia.

Our driving force analysis identified five main factors driving the changes in wind erosion observed over the study period. Precipitation and number of windy days (as main environmental factors) and rural population growth rate, urbanization level, and GDP1 rate (as main human-driven factors) can explain 88.8% of the variation in wind erosion over the period studied. Climate change was the main driver of changes in wind erosion over this period, mainly through an increase in rainfall and a decrease in wind frequency.

Human activity also contributed to changes in wind erosion. Our results showed a reducing effect of human activity on wind erosion in Inner Mongolia. This effect could be achieved through increasing urbanization moderately, promoting the concentration of rural populations in urban areas, reducing the intensity of agriculture and pasture practices, optimizing the industrial structure, promoting forest and grassland restoration from farmland, restricting grassland cultivation, limiting the number of livestock heads on grassland, and allowing a timely recovery for degraded grassland, promoting rotational grazing and corral livestock.

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