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Spatial distribution of wind erosion and its driving factors in China

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Abstract: Based on remote sensing and geographic information system, the spatial distribution of nation-wide wind erosion is studied, and the 1:100 000 national map of soil erosion by wind in China is made. Wind speed, soil dryness, NDVI, soil texture and the slope of land surface are the key factors to wind erosion. The relations between wind erosion and each factor are discussed. The method of principal component is used to pick up the information included in the five factors, and the wind erosion dynamic index (WEDI) is established. Its comparison with the RS/GIS derived data shows that WEDI can reflect the potential capacity of soil erosion by wind. The dynamic process of the wind erosion is studied to reveal the distribution of the most intense wind erosion regions and the dominant factors in these regions. All these studies may greatly help the mitigation of wind erosion of soil.

Spatial distribution of wind erosion and its driving factors in China ZHANG Guo-ping1, ZHANG Zeng-xiang1, LIU Ji-yuan2 (1. Institute of Remote Sensing Application, CAS, Beijing 100101, China; 2. Institute of Geographic Sciences and Natural Resources Research, CAS, Beijing 100101, China) Soil erosion by wind means the soil particles are eroded and transported by wind. Fine particles of soil are transported as suspended load and may travel much greater distances than the coarse coarse materials do which are transported as creep and saltation. The finest particles and chemical microsome constitute the aerosol which can even keep for several years in atmosphere from descending. Wind erosion is a serious problem in many parts of the world. In China, up to 2400 km2 of land is desertified every year[1]. Since 1950, the heavy sand-stormy days of a year have been increasing while the total sand-stormy days is experiencing a long-term decrease[2]. The average soil loss of Northwest China is over 5.0 mm · a-1, while North China has an erosion rate of around 1.0 mm · a-1[3]. The serious soil erosion by wind also causes significant degradation of air quality. Wind erosion research has experienced a long history. Bagnold[4] first established a series of equations to describe the physical process of wind erosion through Wind Tunnel Test, initiating a new stage for the quantitative research work. Different models are yielded to predict the soil loss, among them RWEQ and WEPS are most popular[5,6]. Although yearly prediction, even daily calculation can be carried out, all prevailing models can only be undertaken within a geographically small area with simple land cover and terrain. Nation-wide wind erosion model is still under developing. The remote sensing technique can provide renewable, precise, multiple data of land surface and its changes in a large area where different scales of work concerned with wind erosion can be carried out. Firstly, the outcome of wind erosion process that happened in a certain area can be sensed remotely. Secondly, the information of soil type, land cover and land-use can be picked up. The vegetation coverage of land can also be interpreted. Attention is induced to the satellite-derived estimates of soil water content and evapotranspiration[7,8]. Generally, all the main erosion-driving factors, such as soil type, soil moisture, vegetation cover, land management and its changes, can all be studied by utilizing remote sensing technology. With geographic information system method, the multi-scope data can be performed geographically, by recovering to two-dimensional, three-dimensional, as added time factor, even four-dimensional real time monitoring and special analysis work. The method of Principal Component is up to now one ideal method to pick up the most valuable information from nearly over-bursting data. In this article, the wind erosion dynamic index (WEDI) is constructed based on it. 1 Remote sensing investigation to soil erosion by wind Based on the national TM images, land-use, soil texture, DEM, field data and other information, the distribution of different erosion intensities of wind erosion is obtained following the procedure shown in Figure 1. The wind erosion is classified into six grades: Figure 1 The procedure of investigation of soil erosion 1) Weak erosion (WE): This type is characterized by th e distribution of flecky pits on desertified land and scattered flecky pits on farmland. Basically no erosion occurs on the windward slopes of dunes. The eroded area occupies less than 5% of the total, or the area of floating sand dunes comprises no more than 5% of the total area. The vegetation cover-degree is higher than 50%. The water area is included in this type as well. 2) Slight erosion (SE): Eroded grooves appear in flat desertified land, crevasses appear on the windward slopes of dunes; dense linear wind eroded grooves exist; the eroded area takes up 5-25% of the total area, floating sand sheet and brushy sand dunes take up 5-25% of the total area while vegetation covers 20-50%. 3) Middle-scale erosion (ME): Big eroded holes exist, about half of the windward slopes of dunes have crevasses; middle scale holes exist; the eroded area takes up 25-50%, or the dense floating sandy sheet and brushy sand shares 25-50% of the total area; vegetation cover-degree approximates 10-20%. 4) Intense erosion (IE): Big eroded holes distributing on flat sandy land and crevasses extend to the top of dunes; eroded low land distributes; the eroded area takes up 50-70% of the total or big and tall floating sand dunes and chains of sand dunes occupy 50-70% of the area and vegetation cover-degree approximates 5-10%. 5) Highly intensified erosion (HIE): Deeply eroded low lands and grooves exist, the eroded area takes up more than 70% of the total land; floating sand sheet and sand dunes hold more than 70% of the total land; vegetation covers 1-5% of the total land. 6) Most intensified erosion (MIE): The deepest sheet-like eroded basins exist; large and steep grooves and floating sand dunes take up more than 90% of the total area; vegetation covers less than 1% of the total land, including exposed rocky land and gravel Gobi. Figure 2 shows the result of the nation-wide remote sensing investigation of soil erosion by wind. The MIE covers an area of 52×104 km2, distributing to the south and east of Taklimakan Desert, northern and eastern Xinjiang, and western Inner Mongolia. HIE areas hold up 39×104 km2, scattering in Taklimakan Desert, Tenggar Desert and Badain Jaran Desert. IE areas totaled 37×104 km2, laying over the Gurbantunggut Desert of northern Xinjiang, eastern Xinjiang, Qaidam Basin, Tengger Desert and Badain Jaran Desert. ME areas occupy 38×104 km2, situating at the edge of the deserts that have been listed above. The sandy desertified land such as Mu Us, Hunshandake and Horqin are also experiencing middle-scale erosion. Moreover, the north of Qinghai-Tibet Plateau also suffers middle-scale erosion. The total area of WE and SE is 35×104 km2 and 29×104 km2 each, mostly locating at the edge of desertified land described above, besides the grassland with low and middle cover-degree of vegetation and part of farmland. Figure 2 Result of remote sensing investigation of soil erosion by wind Almost all wind erosion events happen in the arid and semi-arid areas where desert, desertified land and Gobi dominate. As shown in Figure 2, most of these areas are unsuitable for usage. Almost all wind erosion occurs within an area that has less than 400 mm precipitation. The MIE, HIE and IE areas are distributed in the region where the annual rainfall is less than 200 mm. Except for the oases, the region's vegetation coverage is very low, with vast exposed area. The ME, SE and WE areas are mostly in the semi-arid area where the annual precipitation is in the range of 200-400 mm and its vegetation coverage correspondingly increases. The situation is different in Horqin, where the average annual rainfall is more than 400 mm, even up to 800 mm in part of it, but the WE and SE areas take up 95% of the total area. The terrible fact is that bare sandy land, low coverage grassland and low quality farmland dominate the regional land-use. Four regions in the country can be identified through the classification of soil erosion by wind, i.e., Xinjiang, western Inner Mongolia, the middle part of Inner Mongolia and eastern Inner Mongolia. In Xinjiang, with the exception of mountainous areas of Tianshan, Altay, southern Kunlun and oases, all are suffering heavy wind erosion. In eastern Xinjiang, wind eroded basins, big wind eroded grooves and valleys prevail; vegetation coverage is less than 1%; rocky land and gravel Gobi are two main land-cover types. In western Inner Mongolia, like eastern Xinjiang where MIE dominates, vegetation coverage is less than 5%. As for central and eastern Inner Mongolia, WE, SE and ME areas are widely distributed on grassland with middle coverage, most of which are over-grazed. 2 Analysis of key factors to wind erosion 2.1 Distribution of wind field Wind intensity is one of the main factors to soil erosion, operating directly on the transport of soil and sediment[9]. In winter, North China is controlled by the strong winter monsoon. Bursting cold airflow invades to the south, which brings strong wind erosion events. Figure 3 Distribution of land-use and rainfall contour It has been reported that the threshold wind speed for sandy loam, loamy sand and stable sandy soil is 6.0, 6.6 and 5.1 m·s-1 respectively[10]. Giving the same soil environment, the longer the time when threshold wind exists, the more soil loss happens. From the data of 616 meteorological stations in China, the wind information dated from 1981-1990 is picked out for the statistics of the average daily wind speed. The number of days when its average wind speed overpasses 6.0 m·s-1 is counted. The total has been used to form data of yearly wind intensity, as shown in Table 1. Among 616 stations, 365 stations have at least one day when the average wind speed overpasses 6.0 m·s-1 (SD). The total SD from November to next May is summed as SD*, and its comparison with the yearly totaled SD (SDy) is undertaken. Results show that at 289 stations, SD* constituted 60% of SDy, whilst at 170 stations, the SD* constituted 80% of SDy, indicating the period of November to May is the main windy period of China. Ta ble 1 Distribution of days of wind speed exceeding 6m · s-1 Where SD* is the number of days when its average wind speed overpasses 6m · s-1 during November to May of next year, and SDy is the number of days when its average wind speed overpasses 6m · s-1 all the year round. Figure 4 Distribution of wind intensity in China With GIS method, the SD* is spatially interpolated, as shown in Figure 4, which clearly shows that the value of SD* is reducing southeastwardly. Five regions can be plotted out. The first region lies to the conjoined part of eastern Xinjiang, western Gansu and western Inner Mongolia, its SD* value is in the range of 30-45. The second region is distributed over the northwest of Da Hinggan Mountains, Taihang Mountains, and Yinshan Mountains, experiencing SD* of 15-45. In this region, the southeastward wind is partially blocked and weakened by the mountains. The third region lies to the south of Northeast China, its SD* value is less than 30. The fourth region is distributed over most parts of the Qinghai-Tibet Plateau, with its SD* values greater than 30. Some parts of this region have SD* values more than 60. The fifth region lies to the coastal zone of southeastern China. 2.2 Distribution of soil dryness The soil moisture, which in this article is replaced with soil dryness, is another factor which influences wind erosion[11,12]. It directly dedicates to the actual size of soil structural unit. Soil dryness is significantly related to rainfall and temperature, for low rainfall and high temperature may prevent soil particles from aggregating into large units. Formula (1) is used to derive soil dryness: (1) where D is the soil dryness and P is annual precipitation. With the interpolation of the data of soil dryness, Figure 5 is plotted, from which we can see that only relatively dry soil particles are susceptible to drift with wind. Consequently, wind erosion is limited primarily to arid and semi-arid areas. They are almostly concentrated in Northwest China, including Xinjiang, western and central Inner Mongolia, northwest of Qinghai, Gausu, Ningxia and Shaanxi. The most arid area lies to the east of Xinjiang and west of Inner Mongolia. Sub-humid area distributes in eastern Inner Mongolia, southwestern part of Northeast China, North China and western Tibet. Other places, such as southern Qinling Mountains, Southwest China, the northern and eastern parts of Northeast China, are climatically humid. Figure 5 Distribution of land surface dryness China 2.3 Distribution of NDVI Vegetation cover is another factor which influences wind erosion. Besides the water and snow-covered areas, dense vegetation covered land is less sensitive to wind erosion[13]. On the contrary, the poorly covered land is more apt to wind erosion. The density, height and distribution of plants and the decomposition of their residues all influence the speed of the surface wind[14,15]. AVHRR satellite images NOAA-14 are commonly used to calculate the NDVI, as shown by formula (2): (2) where ch1 and ch2 are the data of the first and second channels of NOAA respectively. In our study, NDVI of every ten days of 1992 and 1993 is analyzed to yield information of monthly vegetation changes. As shown in Figure 6, sub-humid and semi-arid areas are all experiencing a dramatic increase of NDVI and weakening of wind speed during summer. As to the arid area, vegetation coverage is less than 5%, wind speed and soil dryness are relatively high, even in summer wind erosion occurs frequently. During winter, the same as the arid area, the semi-arid area suffers loss of originally sparse surface vegetation cover. For most farmland of North China, much of the vegetation residue is buried or diminished due to tillage and intended burning, where the value of NDVI is very low. Figure 6 Distribution of NDVI 2.4 Distribution of soil texture Different sizes of soil particles possess varied shear strength corresponding to its friction speed of wind [16]. It has been reported that particles of clay have stronger tendency to cling together to form big clod[11]. The threshold wind speed of sandy soil is greater than that of loamy soil, whereas the erosion rate of the gravelly soil to the Gobi soil is less than that of the sandy soil[17]. Inversely, the rocky land has a very low erosion rate. According to the texture, different types of soil are classified as shown in Figure 7. The clayey soil mainly distributes within the southeast humid area. This type distributes in the eastern part of Northeast China as well. Loamy soil widely distributes throughout China, with the clay content reducing southeastward and the middle-size (φ) particles increasing northwestward, reaching to the edge of desert. Dune sand and sandy soil are distributing inside and around the desert and desertified land. The gravelly soil is mostly distributed in the Gobi desert, Northwest China. Figure 7 Distribution of soil texture 2.5 Distribution of slope Figure 8 shows the distribution of the slope derived from 1: 1 000,000 DEM map of China. There are topographically three levels of terrain. The first level has an average elevation of less than 500 m, including several large plains. The second level has an average elevation of less than 3000 m, including several plateaus like Loess Plateau, Inner Mongolia Plateau and others, and basins like Tarim Basin, Junggar Basin and others. The third level where the Qinghai-Tibet Plateau is situated, has an elevation of up to 8000 m. The interior of all the three regions are relatively flat while their conjointly areas are characterized by sharp increased slope. Comparing to the distribution of wind erosion shown in Figure 9, the steep slopes have lower erosion intensity, mostly because steep slopes are mainly related to mountains that have dense ridges which can reduce erodibility of the soils[18,19]. Figure 8 Distribution of slope 3 Construction of wind erosion dynamic index (WEDI) The five factors that influence soil erosion by wind have been discussed above, but much information still remains undisco vered. So it is significant to reveal the relations among these five factors and eliminate redundant information. The method of Principal Component is used to pick up information contained in the five factors. According to Principal Component Method, wind intensity, dryness, NDVI, soil texture and slope are taken into account as five variables. Firstly they are all initialized with the following formula: (i = 1, 2, …, n) (3) where (4) (5) Secondly, the relation matrix of five variables is set up according to formula below: (6) Thirdly, the latent root and eigenvectors of the matrix R are calculated, as shown in formula (7): (7) Fourthly, linearly combine all eigenvectors as shown by formula (8): (8) With output of the principal components, the general index can be yielded by the following formula: (9) where Yi is one of the principal components, is the corresponding eigenvector yielded from formula (10): (10) After we input the values of these five factors, their principal components are extracted. Based on the value of eigenvector, the weight of every component is calculated and general evaluation of wind erosion index shown in Figure 9 is gained. The wind erosion index derived from the five factors cannot replace the real soil erosion intensity of wind. However, it can represent potential erosion intensity under the dynamic process determined by the five factors. Here we name it as wind erosion dynamic index (WEDI). From a nation-wide point of view, the distribution of WEDI that significantly accords to the data of soil erosion by wind yielded through remote sensing technique can be grouped into two devisions. One is northwestern China, distributing almost in consistence with the arid and semi-arid area, with WEDI values ranging from 0.8 to 1.3. The other lies in the sub-humid or humid areas of southeastern China, with WEDI less than 0.8. Southeastern China is characterized by low wind intensity, high humidity, high vegetation coverage, fine soil particles and a large area of flat surface. All these factors significantly lead to decrease in erodibility of soil, and increase in soil roughness. But for northwestern China, the conditions are reversed, as shown by high dryness, low coverage, coarse soil and longer strong wind blowing period. However, these two divisions are not completely separate. The value of WEDI is decreasing southeastward, which is in accordance to the distribution of the above-mentioned five factors. A transit zone exists, which mostly covers the semi-arid and sub-humid areas where a fragile ecosystem is struggling to survive with southeastward shifting of mixed agro-pastoral area[20]. Due to expanding cultivation to the originally grassland and forest[21], vegetation coverage in winter and spring drops sharply. Irrational usage of water resource leads to the decline of underground water level and lower soil moisture. All these contribute to a higher WEDI value, and hence a heavier soil loss. The occurrence and development of sandy desertification has been accelerating in the recent century. Human land-use seriously aggravates wind erosion and furthermore affects the living environment and people’s livelihood. From Figure 9, it can be seen that most parts of northwestern China are experiencing serious wind erosion. Figure 9 Distribution of WEDI Different places have varied key factors and dynamic processes, by which six regions can be distinguished, as are described in the following. The region of Northwest arid area is the largest place where serious wind erosion occurs. The value of WEDI is mainly controlled by soil dryness, NDVI and wind speed. The precipitation is sparse and most rainfall occurs in summer and autumn, which makes the condition even worse. Soil suffers a long-term dryness, causing very low vegetation coverage. The strong wind blows on the exposed soil and serious soil loss happens almost in every season. Almost all the areas with WEDI values reaching 1.1 fall in this sub-region. Main deserts, such as Gurbantunggut Desert, Taklimakan Desert, Badain Jaran Desert and Tengger Desert, have the highest values of WEDI. In alluvial and diluvial areas, where Gobi dominates, the WEDI values are also the highest. However, in the main mountain areas, like Tianshan Mountains, Qilian Mountains, Helan Mountains and Yinshan Mountains, the Vertical Zonal Law works distinctly, yielding a reduced WEDI value. For the oases, due to enough irrigation and ample underground water resource, high vegetation coverage and soil moisture, the WEDI value decreases. In the region lies of semi-arid and sub-humid areas of Inner Mongolia. WEDI is mainly influenced by wind and vegetation coverage. The yearly rainfall can meet the basic demand for grass growth. However, diminishing of grassland followed by presently enlarged cultivated land causes low vegetation coverage in winter and spring. Along with over-grazing, strong wind blows off more soil away. For the Qinghai-Tibet Plateau region, WEDI is controlled by the factors of soil surface dryness and snow cover. Intensified wind field exists from the end of autumn to the beginning of next summer. Soil surface temperature is very low due to high elevation which causes soil water frozen. Large permafrost areas exist and soil particles are clung together at that time, dramatically reducing soil erodibility. At the same time, large areas are covered with snow, protecting the soil beneath. The eastern part of the plateau that has a higher rainfall and vegetation coverage possesses a low WEDI value. The northern and western parts of the plateau have low rainfall and dryer soil surface, WEDI is then very high. The fourth region lies in North China, where WEDI is mostly controlled by soil dryness and vegetation coverage. Although long-term average precipitation of a year is 400-800 mm, seasonal variation of rainfall is significant. The rainfall in winter and spring is rare, leading to a dryer soil surface. At the same time, tillage can reduce vegetation coverage. The wind field is moderate, but the wind speed is enough to carry the soil particle. Especially the recent decades, water resource shortage has motivated the over-exploiting of underground water, leading to the increase of soil dryness. As shown by the high WEDI, the stormy weather also occurs frequently[21], driving a desertification process with an average soil loss of 1.0 mm.a-1. In Northeast China region, WEDI is very low, as a feedback to the widely distributed high soil moisture and vegetation coverage. But in the western and southern parts of the region, such as the drainage area of the Liaohe River and the sandy desertified land of Horqin, due to intense conflict of water resource and egregiously expanding of cultivated land, WEDI is high. In the region of eastern, central and southern parts of China, corresponding to humid environment and the highest vegetation coverage, WEDI is very low, with all the values below 0.8. But to the coastal area, sandy land exposes to the strong wind as shown in Figure 4, wind erosion happens as what has been identified by increased WEDI. The distribution of WEDI does not perfectly overlap over the actual situation of wind erosion because the latter results from anthropologic and geologic evolution of long history. However, WEDI reflects the potential erosion intensity of wind. Not all desert or desertified areas have the highest WEDI value, as well as not all farmland or grassland have low WEDI value. WEDI is useful to the wind erosion control. According to the distribution of WEDI, the key areas can be identified. At the same time, regional dominant factors to wind erosion can be studied so as to take appropriate measures. For example, in the strong wind hit regions like cultivated land of central Inner Mongolia and oases of Xinjiang, the shelter belt should be set up and strengthened. In the places where erosion is mainly caused by low vegetation coverage, it is necessary to increase the amount of soil surface residue and soil roughness, and reduce the spoiling of soil structure by over-grazing and military activities. In oasis area, the Loess Plateau, the southern part of Northeast China and the North China Plain, human utilization of water resource should be in harmony with natural environment. 4 Conclusions 1) On the basis of the classification of soil erosion by wind established through remote sensing method, the distribution of wind erosion in China has been investigated. 2) Wind field, soil dryness, NDVI, soil texture and slope are five key factors dominant to wind erosion. 3) Based on the five factors, WEDI is constructed and compared with the results from remote sensing investigation. WEDI reacts sensitively to its five contributing factors. WEDI can be used to study the intensity of wind erosion and its dynamic process. It is also instructive to the actual practice of mitigating and controlling soil erosion by wind. Acknowledgements The authors thank Dr. Xiang Bao for his helpful suggestions. The authors also express their sincere thanks to Zhao Xiaoli, Zhou Quanbin, Liu Bin, Wang Changyou, Zhang Zongke et al. With their hard work, the project of Remote Sensing Investigation of Wind Erosion is fruitfully finished. References

关键词： remote sensing; geographic information system; wind erosion of soil; desertification control in China; WEDI

