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Identification of the key ecological factors influencing vegetation degradation in semi-arid agro-pastoral ecotone considering spatial scales

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A B S T R A C T

When assessing re-vegetation project performance and optimizing land management, identification of the key ecological factors inducing vegetation degradation has crucial implications. Rainfall, temperature, elevation, slope, aspect, land use type, and human disturbance are ecological factors affecting the status of vegetation index. However, at different spatial scales, the key factors may vary. Using Helin County, Inner-Mongolia, China as the study site and combining remote sensing image interpretation, field surveying, and mathematical methods, this study assesses key ecological factors affecting vegetation degradation under different spatial scales in a semi-arid agro-pastoral ecotone. It indicates that the key factors are different at various spatial scales. Elevation, rainfall, and temperature are identified as crucial for all spatial extents. Elevation, rainfall and human disturbance are key factors for small-scale quadrats of 300 m × 300 m and 600 m × 600 m, temperature and land use type are key factors for a medium-scale quadrat of 1 km × 1 km, and rainfall, temperature, and land use are key factors for large-scale quadrats of 2 km × 2 km and 5 km × 5 km. For this region, human disturbance is not the key factor for vegetation degradation across spatial scales. It is necessary to consider spatial scale for the identification of key factors determining vegetation characteristics. The eco-restoration programs at various spatial scales should identify key influencing factors according their scales so as to take effective measurements. The new understanding obtained in this study may help to explore the forces which driving vegetation degradation in the degraded regions in the world.

1. Introduction

Derived from remote sensing images, Normalized Difference Vegetation Index (NDVI) is an accurate indicator of vegetation degradation detection (Evans and Geerken, 2004; Wessels et al., 2012; Karnieli et al., 2013) for riparian landscapes (Mcfarland et al., 2012), sandy land (Zhang et al., 2012), or savanna ecosystems (Jacquin et al., 2010). Several ecological factors can affect vegetation degradation, such as rainfall, temperature, elevation, topological features, and human disturbance (Zhou et al., 2014; Rishmawi and Prince, 2016; Sun et al., 2017). Identification of the main drivers determining vegetation degradation from these biophysical, geographical, and climatic factors has been a core research issue in recent decades. From rainforests to temperate forests, semi-arid, or arid regions, the relationship between NDVI indices and ecological factors (including human activities, biophysical, geographical, and climatic factors) are used throughout the world to identify key factors(Pueyo et al., 2006; Paudel and Andersen, 2010; Wessels et al., 2012; Cao et al., 2014; Tian et al., 2014; Zhou et al., 2014).

Under most circumstances, human activities are found to be primary factors underlying vegetation degradation, followed by climatic conditions. As in a central Mongolian grassland within the past decades, human impact (most probably, overgrazing and farmland abandonment) is the main factor for vegetation degradation at a large spatial scale, whereas climate change and soil erosion play subordinate roles (Tian et al., 2014). To the south of the Mongolian grassland, there is large-sized semi-arid vegetation in northwest China (five provinces), in which 65.75% of grassland degradation was caused by human activities, whereas 19.94% was caused by inter-annual climate change (Zhou et al., 2014) from 2001 to 2010. Human activities were the main factors inducing

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NDVI variation in the Ordos arid region in south-northwest China (Zhang et al., 2014). In addition, a small-scale study in a Mongolian grassland indicated that as the distance from human settlements increased, the vegetation degradation gradient changed from medium to low (Jia et al., 2011), which demonstrated that human activities are the main factors driving vegetation degradation at a small spatial scale as well.

However, human activities can enhance vegetation index, as seen in various case studies. Agricultural development in central Mongolia has greatly increased NDVI in the past decades (Tian et al., 2014). In northwest China, successful restoration projects can improve vegetation NDVI in numerous areas of the Ordos sandy land (Zhang et al., 2014). A study in northwest China (five provinces) indicated 32.32% of grassland restoration was caused by human activities, whereas 56.56% was caused by climatic factors. Obviously, human activities made more contributions to grassland NDVI increase compared with climate change (Zhou et al., 2014). Therefore, human activities result in positive (land restoration and re-vegetation) or negative (degradation) correlation with vegetation index.

Among climatic factors, precipitation is the most influential factor determining vegetation coverage, as revealed by NDVI. In semi-arid grassland ecosystems, principal drivers of NDVI are precipitation amount and timing (He, 2014). Furthermore, the same trends are found in southern Africa (Wessels et al., 2012), Nepal (Paudel and Andersen, 2010), and the Qinghai Lake Basin in China from 2001 to 2010 (Guo et al., 2014). Other climatic factors determining vegetation degradation include average temperature, as in Qinghai Lake Basin (Guo et al., 2014). Moreover, elevation is a primary ecological factor determining vegetation characteristics, such as in the upper catchments of the Yellow River in China (Cao et al., 2014). Previous studies identified other ecological factors contributing to vegetation degradation, including slope, aspect, and soil properties (Pueyo et al., 2006; Cao et al., 2014).

As for the above-mentioned studies, correlation of ecological factors with NDVI has been conducted in different study sites at different spatial scales, ranging from as small as a village to a median regional grassland scale or a large scale covering several provinces. However, few studies have been carried out to examine the effects of spatial scaling-up on the relationships between ecological factors and NDVI until date. Whether correlations depend on spatial scale and the behaviors and ecological factors within different spatial scales affecting NDVI are not well known. In numerous studies on landscape ecology, ecological effects caused by spatial scale have been systematically evaluated (Höpfner and Scherer, 2011; Cunningham et al., 2014). Stefanov and Netzband (2005) found that at spatial extents of 250, 500, and 1000 m, weak positive and negative correlations between NDVI and landscape metrics were present when arid landscape characteristics were assessed for metropolitan Phoenix. High spatial heterogeneity in eco-environmental factors such as slope, aspect, rainfall and land use categories contributed to spatial heterogeneity in ecological conditions. Besides, spatial scale effects have been taken into account for exploring the correlation between vegetation index and response factors, e.g., bird community (Cunningham et al., 2014), surface temperature (Chen et al., 2012), or vegetation pattern (Bradter et al., 2011; Danz et al., 2011). The results reveal that the relationship between vegetation index and ecological factors varies greatly with spatial scales. Spatial scale effects may affect the relationship between vegetation index and ecological factors, which have, however, been seldom mentioned in previous studies.

The aim of the present study is to explore the correlations of vegetation index (indicated as NDVI) with ecological factors (annual average precipitation, annual average temperature, elevation, land slope, aspect, land curvature and such human activity properties as land use type and human disturbance intensity) along a series of spatial scales. Among these analyses, the effects of spatial scales on the correlations between ecological factors and NDVI were identified, and the key ecological factors determining vegetation index at different spatial scales were determined in a semi-arid agro-pastoral ecotone in northern China.

2. Study area and methods

Through the application of various ecological factor maps, effects of spatial scale on the correlation of ecological factors with NDVI were tested for key factors determining vegetation degradation along spatial scale gradient. There were five steps in the process: (i) generating land use landscape and NDVI maps by combining remote sensing image interpretation and field surveying; (ii) based on collected data during step (i), ecological factor maps with the same grain size as NDVI map were generated; (iii) ecological factor and NDVI maps with spatial scales of 300, 600, 1000, 2000, and 5000 m respectively were generated, (iv) in the same spatial extent, NDVI map as overlaid with ecological factor maps and the correlations of ecological factors with NDVI were analyzed, and (v) main factors inducing vegetation degradation were identified.

2.1. Study area

Located in the middle of an agro-pastoral ecotone, Helin County, central Inner Mongolia, China, the study region possesses several advantages that make it appropriate for the study of spatial scale effects. As the interface between farmland and pasture, this agro-pastoral ecotone with total area of 3401 km^2 involves various ecological factors and vegetation with high heterogeneous spatial distribution, which is believed to be one of the most eco-sensitive regions responsive to climate and human disturbances. Therefore, it is an ideal area for studying the correlation between ecological factors and vegetation. With relatively complex composition, the region is characterized by a collection of flat plains, hills and mountains (Fig. 1). The highest elevation is 2031 m.

With obvious wet and dry seasons, Helin County has a semi-arid temperate climate. Its annual average temperature is 5.6 °C with a seasonal average temperature of −12.8 °C in January and 22.1 °C in July. Furthermore, the average annual precipitation is 417 mm with a precipitation of approximately 30 mm in January and 103 mm in July. When compared with summer and fall, the average wind speeds are slightly higher in spring and winter. Besides, no obvious seasonal changes are observed in the average relative humidity for the whole year. Sandy biological communities are supported by the semi-arid climate and grass and shrubs are predominant in this area. Helin County is composed of 9 towns with a population of 0.187 million people and the main income of local people comes from agricultural product and livestock resources.

2.2. Generating ecological factor and NDVI maps

The data of the 2010 LULC of the Helin County area were employed, which were produced from a supervised classification model of atmospherically corrected and geo-rectified Landsat Thematic Mapper (hereafter referred to as TM) imagery. Based on field survey data and two Landsat images acquired in July of 2010, the model was originally developed. By adopting Maximum Likelihood Classification, a posteriori sorting of classes initially derived was performed by the classification system. Besides, geographical auxiliary map layers such as land-use maps, image textures and administrative maps were also applied. There were 7 categories in the final land use classification with a reported overall accuracy of