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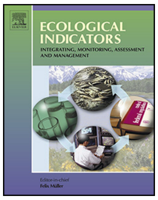

Development of an ecological security evaluation method based on the ecological footprint and application to a typical steppe region in China

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ABSTRACT

The steppes of Inner Mongolia lie in a region which are sensitive to global climate change. The region forms an important ecological barrier against sandstorms and it is also strategically important for the development of China's energy and mineral resources. To describe the influence of resources exploitation on the ecological security of the typical Inner Mongolian steppe, we developed a consumption footprint pressure index (CFPI) and a production footprint pressure index (PFPI) based on the ecological footprint concept, and developed an ecological footprint contribution index (EFCI) to assess the pressures created by transferring resources and products from output areas to input areas. Using these indices, we developed a coupled ecological security assessment model to evaluate the ecological security level of the typical steppe. We used the model to calculate CFPI, PFPI, and EFCI for the steppe area for three counties and one urban region of Inner Mongolia from 2001 to 2010. We found that CFPI and PFPI increased throughout the study period in most regions. In addition, EFCI was generally positive, which indicated the ecological security of the typical steppe was affected primarily by the electricity and production output processes. Our results suggest that the ecological security of the study area has been at serious risk since 2005.

1. Introduction

In China, population growth and socioeconomic development have been accompanied by depletion of energy resources due to excessive consumption (Dai et al., 2010). This has gradually led to serious ecological degradation and environmental damage, which have challenged individuals, communities, and regions. Meanwhile, finding ways to guarantee the health and sustainable development of regional ecosystems despite of rising energy and resource demand has become the focus of research around the world (Hodson and Marvin, 2009), ecological security concept appeared in due course. Ecological security was considered as strategically important as national defense, economic security, and financial security (Andersen and Lorch, 1998; Duffy et al., 2001; Kullenberg, 2002; Bonheur and Lane, 2002). Maintaining global and regional ecological security, and thereby permitting sustainable socioeconomic development, has become the consensus goal of the international community.

Ecological security evaluation is comprehensive, and the main methods that have been used include the pressure-state-response model (Tong, 2000), the system clustering method (Lundquist, 2002), the ecological footprint method (Wackernagel, 1998; Lenzen and Murray, 2001; Huang et al., 2007; Li and He, 2011; Bartel, 2000), the comprehensive index method (Bartel, 2000), the fuzzy comprehensive evaluation method (Onkal-Engin et al., 2004), and the neural network models (Chen, 2004). Among the quantitative methods for ecological security assessment, the ecological footprint method is simple and clear in terms of concept and principles. It has therefore been applied in long-term studies of ecological risk and in regional comparisons (Stoglehner, 2003; Collins et al., 2006; Senbel et al., 2003; Wackernagel et al., 2004, 2006). Also this approach can become an easy-to-read measurement tool for ecological sustainability (Wackernagel et al., 1999), which can also be used to judge whether a country's or a region's development remains within the biocapacity by comparing the consumption and production of resources in the region, thereby reveals the regional ecological security status and the potential for sustainable development (Chen et al., 2010; Liu et al., 2011).

China's Inner Mongolia Autonomous region covers about 12.5% of the country's total land area. It is famous for its lush grasslands and rich mineral resources, and has become main output area of coal resources in China. Given the importance of coal as an energy source in China, the region therefore provides an important contribution to the country's socioeconomic development. However,

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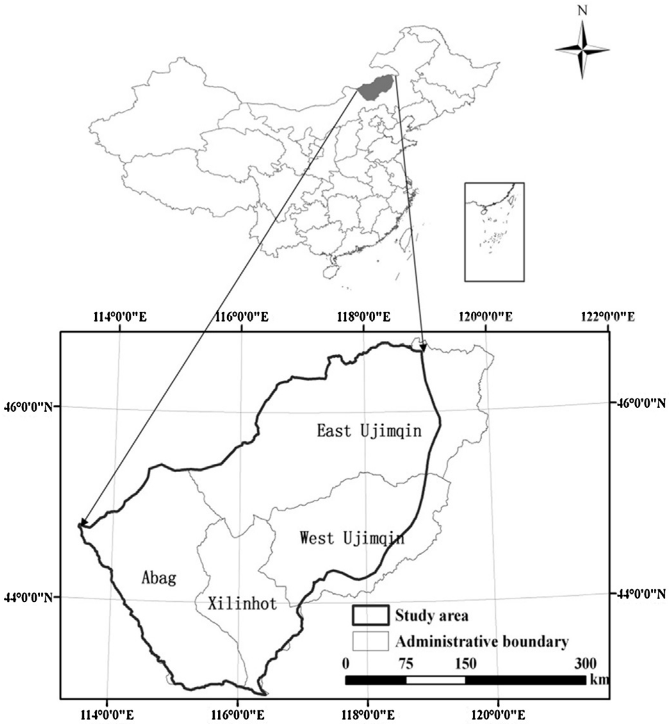

Fig. 1. Location of the study area.

this region also plays a vital role as an ecological barrier in northern China. The typical steppes of Inner Mongolia lie within the Northeast China Transect under the International Geosphere Biosphere Program (IGBP) which is a sensitive area of the global change (Zhang et al., 1997). However, continuous socioeconomic development with excessive exploitation of resources could induce soil and water loss and grassland degradation (Zhu and Qin, 2008; Qing et al., 2013), which threatened the ecological security of the steppes.

In this paper, we will introduce the study area and describe our data sources; provide an overview of the ecological footprint method and the concept of biocapacity, and propose three indices, the production footprint pressure index (PFPI), the consumption footprint pressure index (CFPI) and ecological footprint contribution index (EFCI), which we use to develop a coupled ecological security assessment model and evaluate the ecological security of four typical steppe areas as well as analyze and discuss the implications of our results. The general objective of the study is to measure the pressure imposed by the outside regions to the study area, thereby providing a basis for developing a plan for more sustainable regional development.

2. Study area

The typical steppes in the study were locate in the eastern part of Inner Mongolia, covering an area of 1.1×10^5 km^2 (Fig. 1). Our study area comprises three counties and one urban region: Abag County, East Ujimqin County, West Ujimqin County and Xilinhot City. The study area has a continental arid to semiarid climate, with annual average temperatures of -1 to 4 °C, an annual mean precipitation of 150–450 mm, and an annual evaporation of 1600–2400 mm, which increases from east to west. The elevation decreases gradually from 1800 m in the southeast to 800 m in the northwest. The vegetation is dominated by xeromorphic grasses such as *Stipa grandis* P. Smirn, *Stipa krylovii* Roshev, *Leymus chinensis* Tzvel, *Cleistogenes squarrosa* Keng et al.

The population in the study area had grown gradually, increasing from 3.0×10^5 in 2001 to 3.5×10^5 in 2010. With the rapid socioeconomic development, per capita GDP increased to nine times of its original level, from 1×10^4 RMB in 2001 to 9×10^4 RMB in 2010. Simultaneously, energy consumption had increased rapidly from 0.34 Mt sce (standard coal equivalent) in 2001 to 2.8486 Mt sce in 2010. During this period, the electricity supply increased from 429.36 GW-h to 495.88 GW-h.

3. Methods

3.1. Evaluation model of ecological footprint and biocapacity

Ecological footprint is a kind of simple methodology but comprehensive way for accounting the fundamental conditions for sustainability. It is a resource and emissions accounting tool measuring direct and indirect human demand for the planet's regenerative capacity (biocapacity) and comparing it with the biocapacity available on the planet (Wackernagel et al., 1999; Monfreda et al., 2004; Galli et al., 2012a,b), there are six land-use types for measuring the ecological footprint: cropland, forestland, grazing land, fishing grounds, built-up land, and carbon uptake land (for the absorption of anthropogenic carbon dioxide emissions) (Galli et al., 2012a,b; Borucke et al., 2013) The ecological footprint (EF) can be expressed in the unit of global hectares-gha (Monfreda et al., 2004; Bastianoni et al., 2012; Galli et al., 2012a,b) through a multi-step process, as follows:

$$EF = \frac{Q}{Y_n} \times Y \times r = \frac{Q}{Y_n} \times \frac{Y_n}{Y_w} \times r = \frac{Q}{Y_w} \times r \tag{1}$$

where Q is the amount of a product harvested or CO_2 emitted, Y_n is the national average yield for the product Q (or its carbon uptake capacity in cases where Q is carbon dioxide), and Y and r are the yield and equivalence factors respectively, for the land use type in question. Y is evaluated annually as the ratio of the local yield for production of a generic product (Y_n) to the yield for production of the same product in the world (Y_w) as a whole (Galli et al., 2007).

In order to properly allocate the embodied footprints carried by trade flows of products and keep track of the biocapacity, Consumption Ecological Footprint (EF_C) is calculated by adding the footprint embedded in locally produced products (EF_P) and the imported or input products (EF_I) and subtracting the footprint of exported or output products (EF_E) (Galli et al., 2012a,b; Borucke et al., 2013), to the final footprint value as in Eq. (2):

$$EF_C = EF_P + EF_I - EF_E \tag{2}$$

Among six land-use types, the carbon uptake land is exclusively dedicated to track a waste product: carbon dioxide, since most terrestrial carbon uptake in the biosphere occurs in forests, so carbon uptake land is assumed to be forest land by the ecological footprint methodology (Borucke et al., 2013), as in Eq. (3):

$$EF_{\text{carbon uptake land}} = \frac{P_c(1 - S_{\text{ocean}})}{Y_c} \times r \tag{3}$$

where P_c is the annual anthropogenic emissions (production) of carbon dioxide; S_{ocean} is the fraction of anthropogenic emissions sequestered by oceans, about one-third of anthropogenic emissions are absorbed by the oceans from the total anthropogenic emissions (IPCC, 2001); Y_c is the annual rate of carbon uptake per hectare of world average forest land.

Biocapacity reflects the entire biologically productive area and represents the maximum level of resource supply, which is the counterpart of the footprint (Wackernagel and Rees, 1996;