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Are the drylands in northern China sustainable? A perspective from ecological footprint dynamics from 1990 to 2010

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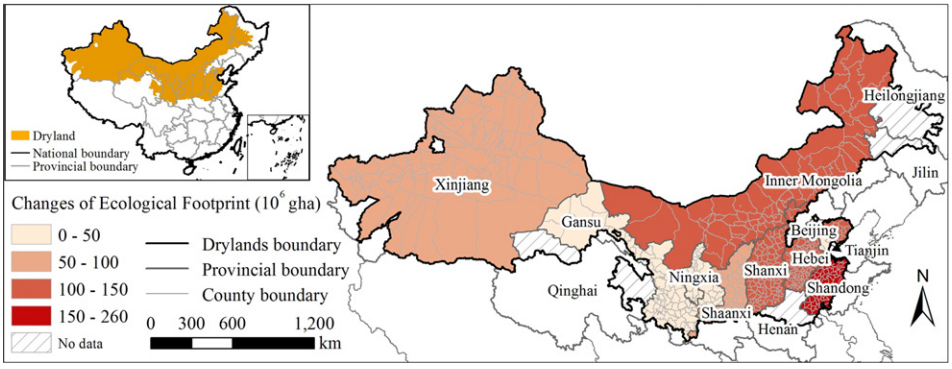
HIGHLIGHTS

- The EF of the DNC was estimated at multiple scales from 1990 to 2010.
- The EF increased from 0.35 to 1.26 billion gha with an annual growth rate of 6.6%.
- Water withdrawal increased from 133.29 to 153.23 km^3 along with the growth of EF.
- The DNC was unsustainable due to the rapid increases of EF and water withdrawal.

GRAPHICAL ABSTRACT



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ABSTRACT

The drylands in northern China (DNC), characterized by water scarcity, high climatic variability, and infertile soil, are crucial for China's sustainable development in the context of rapid urbanization. However, few studies have systematically investigated its sustainability. Our objective was to assess the sustainability of the DNC according to their ecological footprint (EF) dynamics from 1990 to 2010. We analyzed EF in the DNC at multiple scales ranging from the whole, to four dryland subtypes, to the drylands in each province. We found that the total EF in the DNC increased from 3.48×10^8 global hectares (gha) in 1990 to 1.26×10^9 gha in 2010, with a growth of 2.63 times, resulting in a more than 14 times increase of ecological deficit from 6.26×10^7 gha to 9.63×10^8 gha. In addition, the water withdrawal increased from 133.29 km^3 to 153.23 km^3 with a growth rate of 14.96%, while the Human Development Index grew from 0.62 to 0.79. We concluded that the DNC has already become unsustainable after the rapid increases of EF and water withdrawal from 1990 to 2010. We argue that effective management is needed to maintain and improve the environmental sustainability of the DNC.

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1. Introduction

Drylands are areas characterized by a lack of water, which constrains primary production and nutrient cycling (MEA, 2005). More precisely, drylands are areas where the ratio of mean annual precipitation to mean annual potential evapotranspiration is <0.65 (MEA, 2005). Covering 60.95 million km^2 (41.30%) of the Earth's total land surface and supporting more than 38% of the total global population (MEA, 2005; Wu et al., 2015), drylands consist mainly of deserts and grasslands in arid and semiarid regions of the world. Drylands are one of the key areas in relation to sustainable development worldwide due to their vast size and multiple challenges of water scarcity, land degradation, and poverty (Reynolds et al., 2007; Safriel and Adeel, 2008; Wu et al., 2015). Thus, the question of how to maintain and improve the sustainability of the world's drylands has received much attention from the scientific community and society as a whole (MEA, 2005; Wu et al., 2015).

The drylands in northern China (DNC) are facing great challenges because of rapid urbanization (Fang et al., 2008; Wu et al., 2014b). The total urban population in the DNC increased by 63.63%, from 0.11 billion to 0.18 billion, between 1990 and 2010 (National Population Census Office of China, National Bureau of Statistics of China, 1993; 2012). Urban area increased by 68.57%, from 8.05 thousand km^2 to 13.57 thousand km^2, from 1990 to 2005 (Liu et al., 2012) and is likely to increase by more than 25% between 2005 and 2030 (Huang et al., 2014). In the context of rapid urbanization, the DNC are facing the challenge of sustainable development due to their ecological and environmental problems. For example, water demand in the DNC increased from 31.97 km^3 in the late 1980s to 48.19 km^3 in 2010, an accelerating growth of 16.22 km^3 or 50.75% (Liu et al., 2015b), whereas per capita water resources are rather limited, being only 68% of the national average (Chen et al., 2012). Land experiencing desertification in the DNC expanded from 2622 thousand km^2 in 1994 to 2636 thousand km^2 in 2004 (Zhu, 2006; Yang et al., 2008; Xu et al., 2014). The net primary productivity of the semiarid grassland in the DNC decreased from 341.30 Tg C in 1989 to 305.54 Tg C in 2000 (Tian and Qiao, 2014). Additionally, the mean annual fine particulate matter (PM2.5) concentration in some cities in the DNC (e.g., Beijing and Tianjin) was >35 μg/m^3, or more than 3.5 times the Air Quality Guideline of the World Health Organization, in the period 1998–2012 (Han et al., 2015). Therefore, it is essential to assess the sustainability of the DNC in a timely and accurate manner.

Recently, some studies have assessed sustainability in the DNC at different spatiotemporal scales. For example, Liu et al. (2015b) performed a sustainability assessment for water resources in the dryland of northwestern China from the late 1980s to 2010. Xu and Zhang (2012) assessed the sustainability of land utilization in the agro-pastoral transition zone in northern China from 1990 to 2005, and Fang and Xie (2010) conducted a sustainability assessment for the water-constrained urban development in the He-Xi corridor in the DNC from 1985 to 2030 on the basis of socioeconomic indicators. However, sustainability assessment of the DNC remains inadequate because most of these studies focused only on partial regions of the DNC using different indicators. Few studies have examined the sustainability of the whole DNC; thus, the sustainability of the DNC has not been examined completely across different scales with an effective indicator.

Developed by Wackernagel and Rees in 1992, the ecological footprint (EF) has been an effective indicator for systematically assessing regional sustainability (Mayer, 2008; Wu and Wu, 2012; Liu et al., 2015a). EF is primarily a measure of human appropriation of natural resources and is defined as the land (and water) area that would be required to support a defined economy or population, in terms of providing all the energy/material resources for consumption and absorbing all of the wastes discharged (Wackernagel and Rees, 1996; Wu and Wu, 2012). EF is mainly determined by four factors, including the total human appropriation of natural resources, the yield factor, the equivalence factor, and the unit of measurement (Wackernagel et al., 2005; Borucke et al., 2013). By comparing EF to the available bioproductive area (i.e., the biocapacity), sustainability can be investigated effectively at different scales (Wackernagel et al., 2005; Wu and Wu, 2012). For example, Huang et al. (2007) assessed the long-term sustainable development of Shaanxi from its EF dynamics between 1981 and 2008. Xie et al. (2007) assessed the sustainability of Urumqi in 2004 based on EF. In addition, Zhao et al. (2012) assessed the sustainability of Fukang County in Xinjiang between 1971 and 2006 with an integrated method inspired by EF. However, few studies have examined sustainability in the entire DNC using EF.

The main objective of this study was to assess the sustainability dynamics of the DNC from 1990 to 2010 using EF. First, we calculated EF, biocapacity, and ecological deficit at three scales of the whole DNC, four dryland subtypes and the drylands in each province. Then, we examined the sustainability of the DNC from the spatiotemporal dynamics of EF at different scales. Last, we discussed the sustainability of the DNC by investigating the relationship between EF, water withdrawal and Human Development Index (HDI) from 1990 to 2010.

2. Study area and data

2.1. Study area

Covering 3.92 million km^2 and accounting for 40.8% of China's land surface, the DNC are located within 32°52′–53°19′ N latitude and 73°29′–129°25′ E longitude. Between 1990 and 2010, the mean annual temperature within the DNC ranged from −1 °C to 21 °C, with a gradual increase from northeast to southwest. The mean annual precipitation in the DNC decreases from east to west from more than 400 mm to <10 mm (Yang et al., 2008). The mean annual potential evapotranspiration is generally around 8–10 times the mean annual precipitation (Chen et al., 2012; Liu et al., 2015b), with a peak value as high as 3000 mm. In 2010, the population of the area was 0.36 billion people, or 26.7% of China's population, and the gross domestic product (GDP) at the same time was 12.5 trillion yuan, 31.1% of the national GDP (National Bureau of Statistics of China, 2011b; National Population Census Office of China and National Bureau of Statistics of China, 2012). The DNC spans 14 provinces of China, including 745 counties. Following the definition of dryland in the Millennium Ecosystem Assessment (MEA, 2005), the whole DNC can be classified further into four dryland subtypes: hyper-arid dryland, arid dryland, semiarid dryland, and dry subhumid dryland, with consideration of the integrity of the administrative area at the county level (Fig. 1).

2.2. Data sources

Three types of data were used in this research: socioeconomic data, land use/cover data, and auxiliary data. Socioeconomic data for 1990 and 2010 were obtained from the Statistical Database of Economic and Social Development within the National Knowledge Infrastructure of China (http://tongji.cnki.net, accessed September 20, 2014) and included population, GDP, consumption of major foods by rural households, consumption expenditure of urban households, prices for farm products, and energy consumption by region. These data were collected from the China Statistical Yearbook and the China Energy Statistical Yearbook which were published by the National Bureau of Statistics of China. These data were reliable and widely used for calculating the EF in China (Xie et al., 2001). The national land use/cover dataset (NLCD) of China was obtained for 1990 and 2010 from the Data Sharing Infrastructure of the Earth System Science at the Chinese Academy of Science (http://www.geodata.cn/Portal/index.jsp, accessed September 20, 2014). These NLCD datasets were produced at a resolution of 1 km through the visual interpretation of Landsat Thematic Mapper (TM) images (Liu, 2005; He et al., 2014). The auxiliary data, including the administrative boundaries of the nation, provinces, and counties in China at a scale of 1:4,000,000, were obtained from the National Geomatics Center of China (http://ngcc.sbsm.gov.cn, accessed September 20, 2014).