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Analysis

Biocapacity supply and demand in Northwestern China: A spatial appraisal of sustainability

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A B S T R A C T

Integrating spatial analysis with the supply and demand of biocapacity is critical for the sustainable development of regional eco-economic systems. Previous studies have focused on the temporal analysis of biocapacity at broad geographical scales, but lacked the systematic spatial realization at fine scales. An improvement is proposed of this conventional methodology of the ecological footprint by incorporating land-use data derived from high-resolution remote-sensing images into the calculation of biocapacity supply at regional, provincial and county levels in Northwestern China in 2000. The spatial heterogeneity and its effect on the biocapacity supply were systematically revealed for this region. First, the biocapacity supply declined from the east (the Guanzhong Basin and the Loess Plateau) to the middle (the Qaidam Basin and the Turpan Basin), and turned to rise from the middle to the west (the northwest of the Xinjiang Uygur Autonomy). Second, although the gap between biocapacity supply and demand resulted in a small ecological deficit at the regional level, a large ecological deficit was observed at the provincial and county levels, highlighting an unsustainable situation for some of the sub-regions. Importantly, a power law relationship was unveiled between the biocapacity supply and population density, suggesting that (i) the biocapacity supply as a critical indicator could reflect the intensity of human exploitation on local biophysical resources and (ii) humans tend to have a preference to inhabit those areas with high biological productivity. These results provide opportunities to enhance policy development by central and local governments as part of the long-term Great Western Development Strategy of China.

1. Introduction

Sustainable development is a desired policy goal worldwide (WCED, 1987). Within this context, the concept of biocapacity serves not only as a support for social development and human wellbeing (Carey, 1993; Scoones, 1993; Sagoff, 1995; Gao, 2001), but also sets an ecological limit for human activities (Rees, 2006), with its concept rooted in the carrying capacity of the logistic population growth equation (Seidl and Tisdell, 1999). The concept of carrying capacity has evolved through several stages, from population carrying capacity to resource and environmental carrying capacity, on to biocapacity in ecological economics. In the ecological footprint (EF) methodology developed by Rees (1992) and Wackernagel and Rees (1996), biocapacity is defined (Rees, 1992; Rees and Wackernagel, 1994) as the carrying capacity of ecosystems to produce useful biological materials and to absorb waste materials generated by humans. As such, biocapacity stands for a more holistic appraisal of regional ecosystems than other measures (Arrow et al., 1995; Gao, 2001; Yue et al., 2006).

A number of methods have been proposed to quantitatively estimate biocapacity, including net primary productivity (NPP; Lieth, 1972), ecological footprint (EF; Rees, 1992), emergy (Odum, 1996) and a synthetic evaluation based on the analytical hierarchy process (Gao, 2001). Among them, the EF methodology has attracted much attention over the last decade due to its ease of use and compatibility with the data formats from social and economic surveys (e.g., Wackernagel and Rees, 1996; Levett, 1998; van den Bergh and Verbruggen, 1999; Costanza, 2000; Opschoor, 2000; Lenzen and Murray, 2001; Haberl et al., 2001; Senbel et al., 2003; Yue et al., 2006; White, 2007; Kitzes et al., 2009; Kissinger and Rees, 2009, 2010), and has thus been widely applied at the regional level (e.g. ,McDonald and Patterson, 2004; Chang and Xiong, 2005; Yue et al., 2006; Kissinger et al., 2007), national level (e.g., Haberl et al., 2001; Lenzen and Murray, 2001; Wackernagel et al., 1999; Wackernagel and Galli, 2007; Bicknell et al., 1998; van Vuuren and Smeets, 2000) and global level (e.g., White, 2007; WWF, 2008). As a young and still developing methodology, the

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EF calculation requires more integrating design to represent the relationship between humanity and nature (Rees, 2000; Wackernagel and Yount, 2002; WWF, 2006), and the inclusion of spatial structure is thought to meet this requirement, especially with the introduction of the geographic information system (GIS) into the solution (e.g., Wood, 2003; Chang and Xiong, 2005; Yue et al., 2006).

In a standard EF study, biocapacity is often measured by the available area of biologically productive land and water based on data reported in national or regional statistics. A drawback of this methodology is that data often excludes the spatial information of the EF and biocapacity as well as the spatial heterogeneity of natural capital and land use (Erb, 2004). Furthermore, national and regional statistics are often reported at a coarse resolution for political use and may not be applicable for biocapacity assessment at the level of precision required to inform policy making at regional scales (Mayer, 2008; Chang and Xiong, 2005). Concerns over the effect of these blind spots on the spatial assessment of sustainability continue to battle researchers (van den Bergh and Verbruggen, 1999; Opschoor, 2000; Templet, 2000), and an improved methodology that can address these shortfalls is needed (Luck et al., 2001; Jenerette et al., 2006; Kitzes et al., 2009). In this regard, GIS models have been strongly recommended for their ability to provide better estimates than spatially implicit estimates (Kitzes et al., 2009). Therefore, it is possible to use remote-sensing data of land use combined with the spatial analysis techniques in GIS to calculate a spatially explicit biocapacity at both coarse and fine scales, as demonstrated by a few case studies (e.g., Chang and Xiong, 2005; Heumann and Moran, 2006; Moran et al., 2009).

Since 1999, the Great Western Development Strategy of China has been a national policy to ease the national imbalance of economic and social developments, with special focus on the less developed western regions. The implementation of this strategy, together with the ensuing population and economic growth in the region, has caused the impact of human activities on water and land resources to escalate, posing threats not only to the ecosystem, but also to national security. We therefore select Northwestern China (NWC) as a study area for a quantitative and spatial appraisal of the supply and demand of biocapacity. Specifically, we present a quantitative assessment of the spatially explicit biocapacity demand and supply of NWC (covering some 3×10^6 km^2, and containing 5 provinces and 358 counties) at multiple spatial scales, using a combination of techniques from the EF methodology and the spatial analysis in GIS. A series of indices of biocapacity are developed to reflect the integrated status of ecological sustainability at different spatial scales. This study thus refines the current EF methodology and emphasizes the spatial heterogeneity of the regional biocapacity.

2. Method

2.1. Study Area

Northwestern China (NWC) is an arid to semi-arid region lying at 70°02′–110°48′E and 31°47′–45°22′N (Fig. 1A), bordered by Mongolia, Russia and a few Central Asian countries. It comprises the provinces of Shaanxi, Gansu and Qinghai, as well as the autonomous regions of Ningxia Hui and Xinjiang Uyghur, covering a total area of 3,094,730 km^2. It accounts for 32% of China's domestic territory, yet only 7.1% of the whole country's population (89 million according to the fifth Chinese census in 2001), with a third of the population from ethnic minorities (mainly Mongol, Hui, Uygur, Tibetan and Kazakh). The region supports the lowest population density in China, 28.9 persons per km^2. It encompasses a vast expanse of territory including the northern Qinghai–Tibetan Plateau, the middle-western Loess Plateau and the Central Asia Tianshan Mountains. Water resources are scarce and extremely unevenly distributed in the region. Annual precipitation for most of the area is below 400 mm, with the exception of the southern parts of the provinces of Shaanxi and Gansu (>800 mm). The main ecotype is desert and steppe, with a small coverage of forests (9.4% in Gansu, 4.9% in Ningxia, 1.7% in Xinjiang, 0.4% in Qinghai, and 24.1% in Shaanxi). Soil erosion is severe due to both wind and water weathering.

2.2. Ecological Footprint Methodology

The ecological footprint (eco-footprint) for a particular population is defined as the total “area of productive land and water ecosystems required to produce the resources that the population consumes and assimilate the wastes that the population produces, wherever on Earth that land and water may be located” (Rees, 1992). Rees and Wackernagel (1994) also refers to eco-footprint as the ‘appropriated carrying capacity’ (or human demand on nature) and biocapacity as the locally available carrying capacity of the ecosystem. Therefore, the two indicators, eco-footprint and biocapacity, represent the demand and supply of biocapacity. A comprehensive assessment of regional eco-footprint together with an estimate of regionally-available biocapacity gives a good indication of the sustainability of regional social–ecological systems (Wackernagel and Silverstein, 2000; Haberl et al., 2001; Monfreda et al., 2004; WWF, 2004). The ‘ecological surplus’ or ‘deficit’ is defined as the difference between the available biocapacity and the eco-footprint (Wackernagel et al., 2002). This specifies whether a regional population is potentially self-sufficient or is at least partially reliant on imported biocapacity (Haberl et al., 2001).

Given the continuous increase of ecological pressure on the closed system of our planet, the management of human eco-footprint (demand) relative to biocapacity (supply) becomes one of the most important issues of the century (Kitzes et al., 2008). The EF methodology often uses “global hectares” (gha) as a standard unit that represents biologically productive areas with the world average productivity to quantify the eco-footprint and biocapacity, weighing by the equivalence, yield, and fossil-energy conversion factors (Wackernagel et al., 1999; WWF, 2004). The equivalence factor and the yield factor are used to convert the actual area sizes (in hectares) of different land types into their equivalents in global hectares. The fossil-energy conversion factor is the global average energy footprints of various energy categories, and is often used to convert human energy consumption to eco-footprint (Wackernagel et al., 1999). In this study, biologically productive areas are categorized into six main types (cropland, grazing land, fishing ground, forest, built-up area and carbon-uptake land) (Wackernagel et al., 1999; Hansen et al., 2000) and calculated using a weighted sum (in global hectare; Table 1; Fig. 1B). Furthermore, although barren ground (including exposed soil, sand, rocks, snow or ice with less than 10% vegetation cover throughout the year) occupies a large area of approximately 47.8% of Northwestern China (Hansen et al., 2000), we simply considered the biocapacity of barren ground to be zero in the calculation due to its extremely low productivity.

In addition to the three most frequently used EF measures — per-capita eco-footprint, per-capita biocapacity and per-capita ecological budget (surplus or deficit), three further indices were determined – per-unit-area biocapacity, eco-footprint per unit GDP and biocapacity pressure index. The per-unit-area biocapacity is simply the ratio of regional biocapacity to regional land area and reflects not only the efficiency of local land utilization, but also the status of environmental conditions and the productive potential of the land. The eco-footprint per unit GDP is the ratio of regional eco-footprint to local GDP and reflects the efficiency and development level of the local economy. The biocapacity pressure index is the regional eco-footprint to biocapacity ratio and reflects the pressure posed by the human population on the local ecosystem. If the biocapacity pressure index is greater than one, the population is in ecological overshoot, indicating that regional development is not ecologically self-sustaining. If the