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Ecological footprint analysis for urban agglomeration sustainability in the middle stream of the Yangtze River

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ABSTRACT

How to balance ecosystem health and economic development is essential to study sustainability of urban ecosystems. Many methods for assessing urban sustainability have been developed, among which ecological footprint analysis (EFA) has been widely applied as a promising policy and planning tool. This paper proposed a modified EFA with the local ecological footprint being justified by adapting equivalence and yield factors in context of net primary productivity (NPP) from the Miami model. Biodiversity reserves were also incorporated using GIS technology and synthetic assessment of attributes to reflect various ecological functions. In addition, ecological footprint deficit (EFD), implying that the productive land cannot sustain current levels of consumption for a given population, was used to reveal the extent of ecological debt, while the ecological footprint variation index (EFVI) was proposed to describe the tradeoffs between real consumption and the carrying capacity of a specific region. A case study of urban areas in the middle stream of the Yangtze River Basin showed that the per capita EFD of the Wanjiang urban belt, central Poyang Lake urban agglomeration, suburban Poyang Lake urban agglomeration, Wuhan megalopolis, Jingmen–Jingzhou–Yichang urban agglomeration, central Changsha–Zhuzou–Xiangtan urban agglomeration, and suburban Changsha–Zhuzou–Xiangtan urban agglomeration increased by 64.83%, 178.05%, 214.82%, 59.08%, 71.68%, 100.62%, and 91.06% between 2000 and 2010, respectively. The local ecological footprint pressure index (EFPI) was classified into five levels. The Poyang lake urban agglomeration was found to be in a slight deficit, while all others were in a severe deficit in 2010. Calculations of EFVI also revealed that the booming urbanization occurred at great cost to the deteriorating ecosystems between 2000 and 2010. Accordingly, relevant influence factors were investigated using a forward stepwise regression method, which indicated that ecological deficit was positively correlated with GDP, population density, and emission of industrial waste, but negatively correlated with the tertiary industry.

1. Introduction

China is currently undergoing rapid rural–urban transformation, with the total urban population rising from 297.26 million to 712.22 million between 1990 and 2012 (Hillman and Unger, 2013). The emergence of dynamic urban agglomerations has undoubtedly had a positive impact on the economic growth of the country, due to a combination of accelerated industrialization, expanding urbanization, and extensive economic globalization (Kim, 2005; Narayana, 2011). Meanwhile, the dense population and rapid socio-economic development within urban agglomerations have caused excessive depletion of resources and the emission of large amounts of untreated effluents (Angel et al., 2011; Qu et al., 2013; Wang and Bai, 2012), which may result in environmental changes on a global scale, including global warming (Feng et al., 2013; Chen et al., 2014) and atmospheric pollution (Qiu et al., 2014), ecological degradation, and loss of biodiversity (Meffert and Dziock, 2012). For these reasons, long-term planning should focus on the development of sustainable urban agglomerations that comprise a socio-economic human-dominated system at the city level within the capacities of a healthy ecosystem (Browne et al., 2012; Lewin, 2012). Formulated in line with this objective and considering the scientific assessment of sustainable urban agglomerations, sustainable city analysis and policy implementation requires an understanding of the amount of energy and material resources that can be sustainably consumed, directly or indirectly, over the course of a rural–urban transformation (Bodini et al., 2012; Hiremath et al., 2013).

Cities have been described as metabolizing organisms involving the absorption of nutrients, depletion of energy, and discharge of waste since socio-economic processes cannot be independent of the rules of abiotic and biotic systems (Chen and Chen, 2012, 2014). Urban metabolism studies have attempted to quantify the overall

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fluxes of materials and energy within cities, leading to an understanding of the primary loads and the intervention for reducing environmental impact (Chen et al., 2015; Moore et al., 2013). Thus, the notion of an urban metabolism is well suited to the investigation of the footprint, structure, and function of urban sustainability, and balancing the demand for available nutrients with ecosystem conservation. Assessment of urban metabolism can be constructed from a combination of system-based goal functions, such as ecological footprints, ecological resilience, and ecosystem services output, on the basis of modelling of the properties of a human-dominated system, including bottom-up, top-down, and hybrid models (Chen et al., 2014). As a bottom-up model, ecological footprint (EF) analysis has been used widely for sustainability evaluation studies over the past few decades (Medved, 2006; Zeev et al., 2014) because it can be used to calculate the area from which ecosystem services are obtained (Luck et al., 2014) on global and national scales (Fang et al., 2014; Kitzes et al., 2009; Wackernagel et al., 2004; York et al., 2003), to urban scales (Kissinger et al., 2013; Pickett et al., 2001; Rees1 and Wackernagel, 1996), and household scales (Kuzyk, 2012; Sutcliffe et al., 2008). Then, it can be determined whether the consumption and waste production of a region remains within its environmental carrying capacity (Rees and Wackernagel, 1996; Zhao et al., 2005). In addition, Moore et al. (2013) highlighted that both EF and urban metabolism analysis (UMA) utilize material flow analysis, based on the laws of energy conservation and mass balance. Using these properties, EF evaluates the sum of the bio-productive areas directly and indirectly required to provide the energy and material resources for the activities of a population, and to assimilate its resultant waste (Rugani et al., 2014). Six types of bio-productive land can be identified: cropland, woodland, meadow, fishing ground, energy land, and built-up land. These are used to estimate the amount of bio-productive land required to support consumption and waste production (Wackernagel et al., 1999b). In other words, EF tracks the bio-capacity, which is the population of a given species that can be sustained indefinitely in an established habitat without perennially destroying the supporting ecosystem (Bicknell et al., 1998), required to generate the energy and material resources that urban agglomerations consume and to resolve the total waste (Monfreda et al., 2004; Wackernagel et al., 1999b). It should be noted that the bio-capacity characterizes the theoretical maximum sustainable capacity (Siche et al., 2008). An ecological footprint deficit (EFD) – if EF > bio-capacity, cities are in an ecological debt (Monfreda et al., 2004) – by definition indicates environmental degradation, and the ecological capacity barely supports sustainable production. Therefore, it is possible to evaluate the ecological sustainability of urban agglomerations by comparing demand with feasible supply in the EF (Siche et al., 2008).

Generally, EF can be used to estimate the general sustainability of an urban agglomeration, owing to its intrinsic natural-capital accounting metrics and data availability, combined with unified measurements. However, there are some potential improvements for the conditional EF. First, there are no satisfactory and generally accepted global equivalence and yield factors yet (Monfreda et al., 2004) that can represent all types of land productivity among various countries, leading to anomalous results in EF. Liu (2010) used Net Primary Productivity (NPP) values based on Moderate Resolution Imaging Spectroradiometer (MODIS) data to modify the equivalence and yield factors for all provinces within China. However, the yield factor value in energy land was 0, lowering the bio-capacity of this land type. In addition, it is difficult and time-consuming to acquire and interpret MODIS data for local EF at the regional scale, and it is necessary to determine the scalability and veracity of data to estimate NPP. Second, in consideration of the local biodiversity, 12% of available bio-productive land was subtracted from bio-capacity (Wackernagel et al., 1999b). However, accurate total area of biodiversity reserves in a given region can rarely be determined, which results in inaccuracies in the data used for policy making. Finally, the ecological balance between ecological footprint and bio-capacity is a static measure, and does not involve the study of variation; the information provided by such static analysis is extremely limited.

Using a modified EF analysis, this study aims to investigate the urban agglomerations midstream of the Yangtze River basin, as the key development zones in China. The remainder of this paper is organized as follows: the study site is introduced and data source are described; methods for calculating equivalence and yield factors, amended using NPP from the Miami model, are presented; the calculation of the modified local ecological footprint and bio-capacity are described, and three indicators are proposed; the ecological balance, ecological footprint pressure index (EFPI) and ecological footprint variation index (EFVI), which are used to evaluate the sustainability of urban agglomerations, are analyzed; and finally, the implications of the results are discussed.

2. Methodology

2.1. Study site

The urban agglomerations in the midstream Yangtze River basin (MYRB, $26°3'6''$N–$33°29'11''$N; $110°14'39''$E–$119°36'30''$E) consist of five city clusters, namely the Wanjiang urban belt (WJ) in Anhui Province, Poyang Lake urban agglomerations (PL), including its central areas (CPL) and suburban areas (SPL) in Jiangxi Province, Wuhan megalopolis (WH) in Hubei Province, Jingmen–Jingzhou–Yichang urban agglomerations (JJY) in Hubei Province and Changsha–Zhuzou–Xiangtan urban agglomerations (CZX), including its central areas (CCZX) and suburban areas (SCZX) in Hunan Province (see Fig. 1) covering a total land area of 401,500 km^2, with a population of 153 million and a GDP of 988,526.48 million US$ in 2012. The total area of biodiversity reserves is 11,770 km^2. Fig. 2 illustrates the distribution of land use types in 2000, 2005, and 2010, respectively.

2.2. Data sources

Historical data of changes in land-use in the MYRB were computed and analyzed with geometric correction and supervised classification technology based on three Landsat TM images taken in 2000, 2005, and 2010 (see Fig. 2). Meteorological data, including average annual rainfall and annual mean temperature, were primarily derived from *China Meteorological Data Sharing Service System* (http://cdc.nmic.cn/home.do), from 722 weather stations across China from 1971 to 2000. Finally, socio-economic data and other information from 2000, 2005, and 2010 were collected from *China Statistical Yearbooks Database* (http://tongji.cnki.net/overseas/Dig/Dig.aspx).

2.3. Calculation methods

2.3.1. Equivalence and yield factors

Considering the actual conditions of the study sites, it is necessary to compare EF accounts of the different city groups with a universal standard. Equivalence and yield factors can transform different land types in city clusters into equivalent numbers at a regional scale (Kitzes et al., 2007). Thus, equivalence and yield factors are a significant parameter in EF analyses, aggregating multiple values into in a single unit.

NPP can represent the ecological generative capacity of an area (Raich et al., 1991), which has similar characteristics to those of ecological footprint analysis when assessing sustainable regions (Haberl et al., 2004). In recent years, the EF evaluations based on