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Local ecological footprint dynamics in the construction of the Three Gorges Dam

Tianhong Li[a,b,c,*], Xiaoling Wen[c]

[a] College of Environmental Sciences and Engineering, Peking University, Beijing, 100871, China
[b] Key Laboratory of Water and Sediment Sciences, Ministry of Education, Beijing, 100871, China
[c] Shenzhen Graduate School of Peking University, Shenzhen, Guangdong, 518055, China

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ABSTRACT

Modern electricity services rely on long distance transmission from generating sites to end users through a widely connected power grid, which could lead to a “lock-in” of the spatial pattern of energy production and consumption in the development of renewable energy systems. This paper considers the example of the construction of the Three Gorges Dam (TGD) between 1995 and 2008 to investigate the local ecological impacts of such “lock-in” effects in Yichang City, which occupies 51.6% of the Three Gorges Reservoir Area (TGRA), by using a provincial hectare ecological footprint model. The time series of the ecological footprint and ecological carrying capacity from 1995 to 2008 covering the TGRA construction period were calculated with the proposed provincial hectare model. The results show that the local ecological footprint per capita for fossil energy increased up to 3 times despite the completion of the nation’s largest renewable energy project at that time. Although the regional ecological deficit generally decreased at the end of the construction, it is difficult to alter the trajectory of high carbon development afterwards. In conclusion, we suggest studying the local transition of energy consumption at the demand side during construction of renewable energy projects in the future.

1. Introduction

Renewable energy is widely promoted to achieve a sustainable energy transition towards a low carbon society. The most radical strategy is to provide all global energy through wind, water, and solar power (Jacobson and Delucchi, 2011). Most studies focus on the environmental and economic feasibility of replacing the current energy supply with renewable sources (Connolly et al., 2016). However, with an increasing number of large-scale projects established in remote regions with fragile ecological systems supplying the energy consumption in urban centers far away, the broader ecological impacts of the projects on the local environment have been largely ignored.

Moreover, the development of high voltage alternating current (AC) power in late 19th century enabled electricity to be transmitted over long distances from the source of generation to the point of demand, which systematically structured the framework of modern energy infrastructure into a centralized mode of production (Hughes, 1983; Hirsh, 2001). This could lead to a “lock-in” effect in the competition between the generation technologies based on fossil fuels and those based on renewable sources (Goldemberg et al., 1987; Unruh, 2000). Existing research has illustrated the advantage of a distributed generation system fed on the renewable sources, which prefers to put the electricity generation site close to the end users (Akorede et al., 2010). Without awareness of this regime conflict in the electricity industry, the ecological benefits of the renewable energy development can hardly be achieved in contemporary regional and urban planning (Adil and Ko, 2016).

The Three Gorges Dam (TGD) is the world’s largest hydroelectric project in terms of installed capacity (22,500 MW) (Wu et al., 2003). Its construction formally started on 14 December 1994 and it has been completed and in operation since 2009. The TGD was expected to contribute more than 10% of the national electricity consumption and to play a critical role in the low carbon development of China (Xinhua News, 2009). However, due to the dramatic increase of electricity consumption in China, it supported approximately 2.1% of the total electricity demand in China in the year 2011 at full capacity and accounted for approximately 10% of the national generation of renewable energy (National Energy Administration, 2012). Nine provinces and two municipalities consume electricity from the dam, including the most developed regions in China such as Shanghai and Guangdong. The construction of the dam caused significant ecological impacts, not only in terms of physical change of the natural landscape but also in social

* Corresponding author at: College of Environmental Sciences and Engineering, Peking University, Beijing, 100871, China.
E-mail address: lth@pku.edu.cn (T. Li).

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structural changes that resulted in long-term influences on the ecological burden at different levels (Fu et al., 2010). In previous studies, the effects of the TGD on habitat (Gleick, 2009), biotic integrity (Zhu and Chang, 2008; Wu et al., 2010), hydrological regime and ecosystem (Shen and Xie, 2004), and environmental changes (Wen et al., 2017) have been discussed extensively. The ecological footprint method has been used to assess the ecological security in this area too (Wang et al., 2012). This paper aims to highlight the local ecological impacts of such a large-scale renewable energy project by illustrating the dynamics of the ecological footprint and carrying capacity during the construction period of the TGD in Yichang City, which occupies 51.6% of the Three Gorges Reservoir Area (TGRA) in Hubei Province.

An ecological footprint can be defined as a biologically productive land that is used for resource and energy consumption and waste elimination by a particular population and economy (Wackernagel et al., 1999a, 1999b). As both an approach and a method, the ecological footprint was aimed at determining the degree of (un)sustainability of activities and regions/countries (Grazi et al., 2007; Rees 2002, 2003; Tran et al., 2015; Vogelsang, 2002). Many ecological footprint studies have been undertaken with a spatial coverage ranging from local to global (Jeroen and Van den Bergh Fabio, 2013), and a widely sectoral coverage on different industries (Andersson and Lindroth, 2001; Federici et al., 2003; Kasulaitis et al., 2015; Marrero et al., 2017; Xu et al., 2006; Zhang and Zhang, 2004). Most ecological footprint studies employed the global hectare model, in which the parameters are the global available land and average productivity. However, the result of the ecological footprint model is highly sensitive to the spatial-temporal scale, due to the substantial variation in natural resource endowments between different nations or regions (Wackernagel and Silverstein, 2000). Some studies utilize the global hectare scales in smaller civic hectares to match the actual applicability perspective (Gu et al., 2000; Liu et al., 2014; Monfreda et al., 2004; Van Vuuren and Smeets, 2000; Yang et al., 2000; Wu and Wang, 2007; Zhang et al., 2009; Zhang et al., 2000). The calculation of a parameter changed from the initial constant world-average yield method in fixed time to the variable world yield, and then to the variable local yield method. However, the global hectare scale may not objectively reflect the local ecological footprint gap between the demand and supply. Additionally, it is difficult to unify the standards of natural conditions on a global scale without compromising data accuracy at the local level. Therefore, models with a smaller spatial scale are needed (Weinzettel et al., 2014).

In addition, the one-time snapshot could represent only the static condition of the ecological footprints. To address areas with social structural change, time-series analysis of local ecological footprints can be used to capture the change over time (Haberl et al., 2001; Van Vuuren and Smeets, 2000; Zhao et al., 2009).

The paper is organized as following. Section 2 describes the provincial ecological footprint calculation method. Section 3 describes the study area and data processing. Section 4 gives the calculation results on the dynamics of ecological footprints and carrying capacity during the construction period of the TGD. In conclusion, we generalize the pattern of influence on the local ecological burden during the construction of the large renewable energy project. The implication of localized calculation for the ecological footprint will be discussed relative to local actors in the pursuit of more grounded low carbon development.

2. Methodology

Similar to the definition and calculation methods of the global hectare method, the provincial hectare refers to the average productivity in a unit of the ecological productive land area, that is, the amount of biological production. The provincial hectare model uses the basic calculations for the ecological footprint, separating the eco-productive lands that provide human living resources and energy into six categories: farmland, woodland, grassland, water, fossil energy land and construction land (Rees and Wackernagel, 1996; Wang et al., 2012; Yang et al., 2000; Zhang et al., 2000). All the land types use the average productivity of the ecological productive land as a standard. The actual production data determine the equalization factor and yield factor (The actual consumption data for residents in the study area are used to adjust these factors.). Therefore, the ecological footprint and ecological capacity of the provincial standard hectare can be calculated.

When determining the types of the ecological productive land average yield, values for different biological products (such as the per unit weight of wheat and pork) are meaningless and cannot be directly summed up when calculating the average productivity of land. Therefore, the different types of biological products and energy sources are transformed into energy (Lan et al., 2002; Zhang et al., 2016; Zhao et al., 2009).

2.1. Ecological footprint and carrying capacity

2.1.1. Biological resources

Among the six types of ecological productive lands, farmland, grassland, woodland and water are necessary for human survival and development. The areas of these four land types are transformed from consumption by Eq. (1).

$$ef_j = \sum S_j^i \times r_j = r_j \times \sum \frac{C_j^i}{Y_j^i} \tag{1}$$

where ef_j is the per capita ecological footprint of the j-class land within a province; r_j is the equalization factor of the j-class land; S_j^i is the land area which is the i-class product transformed in the j-class land; C_j^i is the consumption per capita of the i-class product in the j-class land; and Y_j^i is the provincial average productivity of the corresponding products.

The biological capacity of these four land types is adjusted by the equalization factor and yield factor using the ratio of various types of land areas and the average productivity of the actual area:

$$ec_j = a_j \times r_j \times y_j \tag{2}$$

where ec_j is the ecological carrying capacity of the j-class land per capita in the province; a_j is the ecological productive land area which is the j-class land per capita; and y_j is the yield factor of the j-class land. According to the World Commission on Environment and Development (WCED), at least 12% of the ecological carrying capacity must be retained to conserve biodiversity (Wachernagel et al., 1999a; Wackernagel and Silverstein, 2000).

2.1.2. Fossil energy land

Fossil energy land is used to describe the pressure caused by human fossil fuel consumption upon ecosystems and for land types that absorb CO_2 and other greenhouse gases. Considering the close relationship between greenhouse gas emissions, fossil fuel consumption, and the global carbon cycle, this study analyzes the ecological footprint of fossil energy in the carbon cycle as did Xie et al. (2008a). Because absorption capacities of woodland, grassland and farmland are different with different land equalization factors, the CO_2 absorption was considered separately for each land type. Farmland is constantly absorbing and also releasing substantial amount of CO_2. Li (2002) and other studies have shown that the absorption into and emission from farmland nearly offset each other. Therefore, only the CO_2 absorption area of woodland and grassland are considered in the present study.

$$EF_{ce} = EF_{ce1} + EF_{ce2} = \frac{C_{ce} \times H_{ce} \times C_{dce} \times P_{erf}}{\overline{EP_f}} \times r_f + \frac{C_{ce} \times H_{ce} \times C_{dce} \times P_{erg}}{\overline{EP_g}} \times r_g \tag{3}$$

where EF_{ce} is the ecological footprint per capita in one fossil energy land, hm^2; $EF_{ce1}$is the ecological footprint of a fossil energy by woodland, hm^2; EF_{ce2} is the ecological footprint of a fossil energy by