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Assessment and prediction of environmental sustainability in China based on a modified ecological footprint model

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ABSTRACT

This study analyses the environmental sustainability status of China using a modified ecological footprint (EF) method which takes into account the freshwater ecological footprint, improves the energy ecological footprint, and amends the equivalence factor and yield factor. Then the linear autoregressive integrated moving average (ARIMA) and non-linear artificial neural network (ANN) models are applied to predict future ecological security. The results show that: (1) The *per capita* EF increased by three times from 1978 to 2013, whereas the *per capita* ecological carrying capacity experienced only a slight increase although the equivalence and yield factors were both enhanced. (2) The 'degree of ecological security' appeared to show a tendency to increase, indicating that China is in a 'pretty unsafe' ecological state. (3) EF intensity, which is used to represent the resource consumption level corresponding to unit economic output, indicated that the utilisation ratio of Chinese natural resources was greatly enhanced during the study period. (4) The ecological footprint diversity index, and ecological and economic coordination coefficient, peaked in the 1990s and then began to fall, indicating that China's ecological environment, as well as its coordination with the economy, was considered to be better in the 1990s but then gradually deteriorated. (5) The predictions of ARIMA–ANN model indicated that the degree of ecological security in China would reach an unsafe state in a few years if certain effective measures were not taken. These findings could be helpful for decision-makers as they strive to make a better package of plans to ensure an ecological balance and a more sustainable future.

1. Introduction

Sustainable development is a hot issue all around the world (Wackernagel et al., 2004a,b). To date, many methods have been proposed to quantify sustainable development, including Material/Substance Flow Analysis (Huang et al., 2006; Barles, 2009; Browne et al., 2011; Yuan et al., 2011; Wu et al., 2012; Huang et al., 2012; Calvo et al., 2016), Life Cycle Assessment (Guinee et al., 2010; Sara et al., 2017), Emergy Analysis (Vega-Azamar et al., 2013; Yu et al., 2016), and Ecological Footprint (EF) (Erb, 2004; Graymore et al., 2008; Zhou and Imura, 2011; Galli et al., 2012; Geng et al., 2014; Miao et al., 2016; Marrero et al., 2017). Among them, Material/Flow Analysis uses mass (*e.g.*, tonnes) as a metric to assess material inflows and outflows, but the same mass does not mean the same function with regard to economic development (Yu et al., 2016). It is crucial to enable quality distinctions between various resources (Matthews et al., 2000; Huang et al., 2006). Life cycle assessment aims at quantifying environmental impacts and resource consumption of a product or service and their relevant processes from "cradle to grave"; however, it is a typical bottom-up environmental tool, containing only up-stream and downstream data about a product or service. Thus, it cannot embody indirect flows outside the system boundary (Reap et al., 2008; Dong et al., 2016). Emergy analysis is a bio-centric method used to assess intrinsic natural resources, nevertheless, but it has been criticised due to its methodological limitations. For instance, the lack of region-specific transformation (known as transformity) data leads to the uncertainty for accurate emergy accounting of various economic products and services. Moreover, transformity is a path-dependent coefficient, which means that the same product can be produced by different production routes and result in different transformities (Baral and Bakshi, 2010). With regard to EF, it uses a land-based indicator on assessing resource sustainability, namely, the amount of bioproductive land needed to

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ensure supply for a given population or system (Wackernagel and Rees, 1996). Although the EF has been widely used as an effective instrument to measure ecological pressure and ecological carrying capacity, it is also criticised for oversimplifying a static perspective of resource use and cannot reflect the variability of population, technological improvements, and material consumption (van den Bergh and Gruzi, 2010; De Alvarenga et al., 2012). Even so, EF is able to reflect, in part, the human appropriation of ecologically bioproductive areas following traditional geographical and ecological principles (Shao et al., 2013). As Senbel et al. (2003), Chen et al. (2010), and Gao and Tian (2016) noted, EF provides an indirect index for the long-term ecological status and an early warning for potential ecological risk. Moreover, EF has the advantages of a transparent accounting metric, readily available data, and a standardised method of measurement (Hopton and White, 2012; Lei et al., 2012; Galli et al., 2012; Miao et al., 2016). Additionally, it should be noted that some researchers have made the improvements necessary to address its shortcomings. Therefore, it should be acknowledged that EF is a simple, but comprehensive, measure of environmental sustainability.

EF, which was developed by Wackernagel and Rees in 1996, reflects how much of the regenerative biological capacity of one general area is needed by human activities (Kitzes and Wackernagel, 2009). It calculates the ecological footprint of human consumption and the ecological carrying capacity of land supply based on a set of relevant quantified indices. Both can be compared to evaluate the environmental sustainability of the research subjects (Hopton and White, 2012; Butnariu and Avasilcai, 2014; Galli, 2015). This method has received a considerable amount of attention and is widely used for sustainability assessment within a certain period of time in some regions (Holmberg et al., 1999; Harber et al., 2001; Chen and Chen, 2007; Huang et al., 2007; Begum et al., 2009; Galli et al., 2012; Hopton and White, 2012; Li et al., 2016); however, trends in EF development and ecological security in the future were not discussed in that research. Senbel et al. (2003) explored the factors affecting EF in North America and predicted an ecological deficit over the coming century. However, their method of scenario analysis was rather random and had a large uncertainty. Yue et al. (2006) applied the rate of change and scissors difference to quantify the trend in EF from 1991 to 2004, and to predict it thereafter. However, the relative errors involved in the rate of change and scissors difference increase as the data volumes grow, moreover, the method's applicability conditions are too strict in some extreme situations. Taking Henan Province in China as the study area, Jia et al. (2010) computed the EF and EC from 1949 to 2006 and used the ARIMA model to forecast the EF indicator. However, the real time-series data is rarely purely linear or non-linear (Zhang, 2003; Khashei and Bijari, 2011). In addition, some traditional regression methods (grey system theory, system dynamics, *etc*.) have been applied to forecast EF, but the accuracy decreases markedly with an increase in the amount of data (Zhang et al., 2008; Lu et al., 2010; Zhu et al., 2011).

As mentioned above, real-world time series often integrate both linear and non-linear patterns. EF, moreover, reflects complex environmental problems and so as that single model may not be adequately to capture its characteristics. ARIMA model has been widely employed for time series forecasting, even though their accuracy is variable owing to their linear representation of non-linear systems (Goyal et al., 2006; Wang et al., 2012). The ANN, which uses a multi-layer perceptron architecture, has been developed as a non-linear tool for time-series forecasting (Pérez and Reyes, 2006; Thomas and Jacko, 2007; Zhang, 2011; Xie et al., 2012). Using hybrid model combined several models with different characteristics has become a common practice to overcome the limitations of single model and enhance the forecasting accuracy (Tseng et al., 2002; Zhang, 2003). To date, the hybrid techniques have been widely used in some studies (Tseng et al., 2002; Aslanargun et al., 2007; Koutroumanidis et al., 2009; Khashei and Bijari, 2011; Liu et al., 2012; Babu and Reddy, 2014; Shukur and Lee, 2015). Thus, in this paper, a hybrid approach, combining the ARIMA and ANN models, is also developed to predict EF time-series data.

Overall, the aims of this study are to: (1) improve traditional EF accounting and make the assessment of China's environmental sustainability more reasonable; (2) develop a hybrid model to predict EF time series data so as to evaluate and predict China's ecological security (and thus provide a reference method for decision-making to derive further ecological protection measures).

The remainder of this paper is organised as follows: Section 2 presents the modified EF model and the forecasting model combining ARIMA and ANN methods, as well as data sources, Section 3 presents the empirical results, and the conclusions are summarised in Section 4.

2. Methods

2.1. Modified ecological footprint accounting

EF is a resource and pollution emissions accounting tool to measure human consumption on the planet's regenerative capacity. The land requirement that makes up the EF is divided into six main area types: (1) cropland to provide plant-based food for grains, fruits, vegetables and oil products; (2) grazing land to provide animal-based food; (3) forest areas to provide timber and other forest products; (4) fishing grounds to provide fish-based food; (5) fossil energy land for the absorption of CO_2 emissions from fossil-based energy consumption; and (6) built-up areas to provide infrastructure for industrial activity, transportation, and housing. EF is a flow indicator and each individual flow can be translated into the corresponding appropriation of bioproductive land area, as described by the following equation:

$$EF = \Sigma r_j(aa_i) = \Sigma r_j\left(\frac{C_i}{P_i}\right) \tag{1}$$

where EF is the per capita EF (ha); i is the consumption item (i = 1, 2, …, n); r_j is the equivalence factor of land of type j, which can be obtained from the literature (Wackernagel and Rees, 1997; Wackemagel and Yount, 1998); aa_i is the productive land area converted from consumption item i; C_i is the amounts of *per capita* consumption for item i (kg/ha) which is affected by the productivity and trade balance amount; and P_i is the average productivity of item i (kg/ha)in a certain area in a certain year.

The quantity ecological carrying capacity reflects the ability of available land resources to sustain anthropogenic activity and is calculated using:

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

where EC is the *per capita* ecological biocapacity (ha); a_j is the *per capita* biologically productive area of land type j in a region; and y_j is the yield factor of that type of land, again obtainable from the literature (Wackernagel et al., 2004a,b).

As for the majority of the existing methods that evaluate sustainability, traditional EF accounting has been improved, as shown below:

(1) Fresh water is not included in the traditional footprint accounting though water resource sustainability is highly concerned by the international scientific community (Chambers et al., 2000; Wang et al., 2013), however, the EF method fails to provide the average yield factor and equivalence factor for freshwater (Hang et al., 2008; Wang et al., 2013). Moreover, with rapid socio-economic development, the problem of water pollution has been paid more attention in China (and is increasingly becoming the main environmental problem). The research of Hang et al. (2008) incorporated reproduction and consumption of water resources into traditional EF, and there are many studies focused on the reproduction of the consumption water resource ecological footprint in different areas