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ANALYSIS

Modified ecological footprint accounting and analysis based on embodied exergy—a case study of the Chinese society 1981–2001

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ABSTRACT

The resource consumption of the Chinese society from 1981 to 2001 is investigated by ecological footprint (EF) as an aggregate indicator. Based on the theory of ecological thermodynamics, a modified calculation of ecological footprint termed as embodied exergy ecological footprint (EEEF) in contrast to the conventional one is performed and related overall trends of the Chinese society 1981–2001 are analyzed. The annual policy for the individual sector is described in detail corresponding to the EF and EEEF components. Comparison of the conventional EF and the EEEF based on different views of ecological production is outlined. The EF intensity and EEEF intensity are also presented to depict the resource consumption level corresponding to unit economic output. Finally, EEEF is suggested to serve as a modified indicator of EF towards illustrating the productions of the resource, environment, population and thereby reflecting the ecological overshoot of the general ecological system.

1. Introduction

There is ecological limit which cannot be exceeded concerning sustainability, posing unparalleled challenges on each level of the ecological system. Therefore, natural capital accounts focused on biophysical limits are increasingly prominent. Meanwhile, there is a felt need for the scarce productive land to support the social–economic–ecological complex system.

1.1. *Ecological footprint*

Vitousek et al. (1986) attempted to determine the human economy's draw on terrestrial net primary productivity and estimate the magnitude of human appropriation of the products of photosynthesis. The total estimation made by Vitousek is regarded as a conceptual predecessor of the EF, which assesses the relationship between the human and the resource (Wackernagel and Monfreda, 2004). Wackernagel and Rees (1996, 1997) proposed the ecological footprint (EF hereafter) as an indicator of the carrying capacity of regions, nations and the globe, and sometimes extended it as an indicator of sustainability. As is defined by Wackernagel and Rees (1996, 1997), the EF is the aggregate area of land and water in various ecological categories that is claimed by participants in that economy to produce all the resources they consume, and to absorb all their wastes they generate on a continuous basis, using prevailing technology, and later, the concept is modified a little as a measure of how much biocapacity a population, organization or process requires to produce its resources and absorb its waste using prevailing technology (Wackernagel and

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Monfreda, 2004). Wackernagel and Silverstein (2000) believed that the EF was consistent with the basic thermodynamic principles, thereby avoiding arbitrary weighting.

In addition, as Wackernagel and Monfreda (2004) emphasized, ecological overshoot is the core concept of the sustainability, i.e., the natural capital is harvested faster than it regenerates, which leads to depleting the resource stock. Unlike the optimists of technology who think technical progress will reduce the ecological deficit or promote the carrying capacity, the technological advances seem to mask the increasing resource scarcity more than solve it (Wackernagel and Silverstein, 2000).

Although the EF has been widely regarded as an effective and easy tool to measure the consumption of the resource and carrying capacity, an extensive academic debate on the interpretation of the EF emerged. Fora for the EF were therefore provided in Ecological Economics and some commentaries and thoughtful discussions were presented (Bergh and Verbruggen, 1999; Wackernagel et al., 1999; Costanza, 2000; Ayres, 2000; Deutsch et al., 2000; Herendeen, 2000; van Kooten and Bulte, 2000; Moffatt, 2000; Opschoor, 2000; Rapport, 2000; Rees, 2000; Simmons et al., 2000; Templet, 2000; Rees, 2000; Wackernagel and Silverstein, 2000; van Vuuren and Smeets, 2000). Whether it can be regarded as a single dimension to measure ecological carrying capacity, sustainability or a basis for equity is still in debate. The EF, at the very least, reflects the human appropriation of ecological system bioproductive areas followed the traditional geography and ecology. As a tool for communicating human dependence on life-support ecosystems (Deutsch et al., 2000), the EF approach can serve as a simple and vivid indicator of ecological evaluation on natural capital and normalize different type of bioproductive area into common units of global hectares.

There are some potential improvements in the current EF method. First, as Bergh and Verbruggen (1999) pointed out, the physical consumption-land conversion factors function as implicit weights in the conversion as well as the aggregation, which impede the application of EF as an objective indicator in ecological evaluation without any arbitrary components. Second, ecological evaluation indicator should reflect both the quantity and quality of the resource, not just a hypothetical land area derived from the quantity of biomass produced from different types of bioproductive areas, and thus cannot distinguish the physical ecological degradation, lost and cost in natural capital, whereas the resource quality is the intrinsic value of the ecological products and the core of the sustainable or unsustainable development mode of the ecological system, e.g., land system. Third, to avoid the debate on the land required to absorb carbon (Ayres, 2000), alternative method should be presented to determine the ecological footprint caused by energy, especially fossil fuels. Although the energy produced from nuclear electricity and renewable resources, such as wind power, water power, photovoltaic and tide power, etc. are roughly investigated by Wackernagel and Monfreda (2004), the related estimation is based on some local case studies, which is still uncertain for the other regions or nations. Finally, as Wackernagel and Monfreda (2004) indicated, embodied energy should be considered, especially the free energy source dominated by the energy embodied in most renewable resources infrastructure.

In fact, although Erb (2004) assessed the EF based on actual area demand which is expressed in physical hectares based on the country-specific yields contrary to the conventional EF approach, the global average hectare is more necessary and valuable in view of the system ecology, for the regions and nations are not isolated in a integrated global ecological system, in which they interacted with and sustained each other through the "share of globally available biocapacity".

Moreover, how to determine the system and environment is the crucial point to assess the validity of EF as an indicator of ecological evaluation. With respect to the time and length scales, depending on the researcher's objectives and knowledge, the sense of the EF can be interpreted in different ways as a unified indicator. With the fundamental time scale of the ecospherical evolution and space scale of the global earth, the EF can serve as an indicator of sustainability, for each global hectare as ecological component is formed and sustained by the others. Meanwhile, on the smaller time and space scales, e.g., nation or region level, the EF can be regarded as an indicator for ecological competitive power, for the limited commodities appropriated by the human and the "actual land area" human demanded are out of consideration for the anthropogenic, temporary and local economic views, not the earth-centered ecocentrism (Chen, 2005, 2006). As Wackernagel et al. (2004a) indicated, the EF can be measured by either consumption or production. Associated with the EF based on consumption, the concept "ecological deficit" is proposed, whereas the concept "ecological overshoot" is presented based on production. Considering a country with much less net import compared to the domestic production, which can be termed as "production-based" country, the concept "ecological overshoot" is more appropriate to reflect the ecological resource depletion of the country. On the other hand, regarding a country with much more net import compared to the domestic production, which is termed as "service-based" country, the concept "ecological deficit" seems to describe the seized resource fraction of the country from the "global ecological hectare share", which should be understood as ecological competitive power.

As Vitousek et al. (1997) emphasized, the use of land to yield goods and services represents the most substantial human alteration of the structure and function of the Earth ecosystem, which is necessary to be measured aggregately. The conventional EF method roots in the "land production" perspective, of which the ecological input of the system, e.g., globe, nation and region, includes all resources transformed by the bioproductive areas. Considering a larger production-supporting scope, the concept of the ecological input can be extended and the EF method thereafter be generalized in the "environment production" perspective. Except for the free natural resources, the emission associated with environmental impact that is necessary to be assimilated by the parallel environment to support the production procedure, termed as sink capacity by Nelson (1995), can be defined as the virtual environmental input for the concerned system, which acted as an additional arm to Odum's three-arm production diagram (Odum, 1996), combining the natural resource input as the sum of the total ecological input.

Based on the classification of different subjects, the ecological system can be classified as human-dominated