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Tracing natural resource uses via China's supply chains

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A B S T R A C T

This paper makes an in-depth analysis on demand-driven natural resource requirements in China via the methods of thermodynamic input-output analysis and structural path analysis, in order to reveal the connections between the country's rapid economic development and its intensive use of natural resources. The main natural resources investigated include crops, forestry, rangeland, aquatic products, coal, crude oil & natural gas, ferrous metal ores, nonferrous metal ores, nonmetallic minerals and other primary energy, and exergy is adopted as a common metric for the resource accounting. In 2012, the total domestic resource exergy input into Chinese economic system amounted to 130.1 EJ, of which 44.6% was induced by investment demands. The embodied resource use (ERU) in China's exports was equivalent to over one fifth of its domestic resource supply. The two integrative sectors of *Manufacturing* and *Construction* accounted for 44.1% and 28.7% of the national total ERU, respectively. We identified critical supply chain paths starting from resource extraction to final demand, as well as key industrial sectors in driving the extraction, transmission and final use of embodied resources. The top 50 paths were responsible for 30.4 EJ of the ERU. The identification of resource supply chains from a systemic perspective is of great importance when resource and environmental policies are to be applied to concrete industrial sectors and other economic agents. Integrated approaches that take account of consumption-based resource indicators should be developed for resource conservation and cleaner production, particularly for the economic system with a complex supply network.

1. Introduction

The operation of socio-economic system has a strong dependence on natural resources as the material basis. Wiedmann et al. (2015) found that “*with every 10% increase in gross domestic product, the average national material footprint (the global allocation of used raw material extraction to the final demand of an economy) increased by 6%*”. In the past two decades, China has used natural resources at a level never seen before. As the largest primary energy producer in the world, China extracted 44.2 billion tons of raw coal, 3.0 billion tons of crude oil and 1217.4 billion m^3 of natural gas during 2000–2015 (CSY, 2016). The outputs of crude steel, ten major nonferrous metals, motor vehicles, ethylene, cement, plate glass, electricity, chemical fiber and primary plastic in 2015 were respectively 6.3, 6.5, 11.8, 3.6, 3.9, 4.4, 4.2, 6.4 and 6.6 times of those in 2000 (CSY, 2016), thanks to the unprecedented resource supply. The utilization of natural resources to sustain modern economies is an irreversible course (Nguyen and Yamamoto, 2007), while the environmental and climate impacts always occur at various stages through resource extraction, processing, conversion, transportation, to end use. China's large-scale exploitation and utilization of natural resources, especially nonrenewable resources, have resulted in adverse effects on the environment including unprecedented resource depletion, severe air pollution and huge greenhouse gas emissions. The effective measures to reduce materials footprint and related ecological impacts are of great concern to gauge the sustainability of the society and support policy making.

Consumption demands are the real driving forces for the extraction and supply of natural resources. The resource fluxes extracted from natural ecosystems are inputted to the socio-economic system through the extraction sectors, and then are processed and used in the industrial sectors along the supply

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chains, and finally are consumed for final users. Since resource requirements can ultimately be attributed to final consumption activities (Zhang et al., 2013), it's necessary for an additional focus on the consumption-based accounting for China's natural resource use by pinpointing the underlying economic drivers (Chen and Chen, 2010). The environmental extended input-output model establishes a direct connection between material production and consumption, and allocates upstream resource extraction to the final demand (Miller and Blair, 2009). To track both direct and indirect effects as embodiment in an economic system, the environmental extended input-output analysis (EEIOA) has been widely applied to explore the land, water, carbon, energy, and ecological footprint at different scales from international trade, national economy, specific industrial sectors to regional or urban economies (e.g., Hawkins et al., 2015; Feng and Hubacek, 2016; Chen and Chen, 2013; Chen et al., 2017; Sun et al., 2017; Wu and Chen, 2017). The embodied resource use or embodied consumption of natural resources provides a metric of economy-wide material flow accounting, which does not record the actual physical movement of materials along the supply chain, but instead enumerates the link between the beginning of a production chain (where natural resources are extracted from the natural ecosystem) and its end (where a product or service is consumed in the economic system).

Structural path analysis (SPA), which enables to excavate the specific supply chain paths in an economic system (Lenzen et al., 2012; Yuko, 2012), has obtained broad application in examining how the final consumption drives the resource uses and environmental emissions (Treloar, 1997; Yang et al., 2015; Lenzen, 2016). The SPA method provides an exhaustive map of supply chain linkages between original production and consumption attributions of resources and environmental elements (Skelton et al., 2011). In recent years, the SPA has been used to analyze flows of energy, water and emissions of air pollutants and greenhouse gases throughout the entire production process of the supply chains at the national scale (e.g., Llop and Ponce-Alifonso, 2015; Meng et al., 2015; Zhang et al., 2017a, 2018b). However, few studies have focused on the overall resource linkages among the mining sector, production process and final demand with the help of EEIOA and SPA methods, partly due to the limit of accounting method for different resource types.

As the combination of the first and second laws of thermodynamics, exergy is defined as the maximal amount of work which can be produced by a system such as a flow of matter or energy carrier as it comes into equilibrium with a reference environment (Sciubba and Wall, 2007). For each type of natural resource, its potential usefulness or ability to perform work is expressed by its exergy content (Szargut, 2005; Warr et al., 2008). Exergy makes it possible to develop a unified metric for evaluating the various types of natural resource (Wall, 1977; Sciubba, 2005; Chen et al., 2006; Dincer and Rosen, 2007; Rosen et al., 2008; Dewulf et al., 2008). In contrast to energy, which can never be consumed according to the conservation law, exergy represents available energy, and is consumed or destroyed due to the irreversibility inherent in all physical processes. Exergy is the “real resource” and “scarce resource” that is used to sustain the development of human society (Chen, 2005, 2006; Hermann, 2006). As a result, the double counting problem existing in energy based methods, like the emergy method, can be avoided in resource exergy accounting (Chen, 2006). In recent decades, the exergy analyses of the Chinese society have attracted extensive attention (e.g., Chen and Chen, 2006, 2007; Zhang et al., 2012, 2018a; Shao et al., 2013; An et al., 2014). Some studies had used the thermodynamic input-output network model to analyze the resource consumption of a country and resource intensities of specific industrial sectors (e.g., Ukidwe and Bakshi, 2004, 2007; 2008; Chen and Chen, 2010; An et al., 2015; Zhang et al., 2017b). Nevertheless, there is still a lag in relation to knowledge concerning the economic drivers of China's natural resource requirements based on exergy.

This paper aims to perform a consumption-based accounting of natural resource uses in China, and explore how the final demand drives the domestic extraction of natural resources, by using EEIOA and SPA methods. Exergy is adopted as a unified way to account different types of natural resources. In order to excavate and depict the complex resource linkages in the economic system network, the dominant supply chain paths of embodied resource exergy flows starting from original extraction to final demand will be identified. A consumption-based resource indicator provides the additional insight to understand the demand-driven resource requirement and inform policies for sustainable resource and supply chain management.

2. Methodology and data sources

The basic row balance for China's national input-output table can be expressed as,

$$X = AX + F - X^m \tag{1}$$

where X is the total output, in terms of a column vector; A is the technology coefficients matrix; F is the final demand vector (i.e., rural and urban household consumption, government consumption, gross capital formation, exports and others); and X^m is the imports, in terms of a column vector.

As to the sectoral allocation for domestic production, the import items should be removed to isolate the domestic supply chain. Referring to other similar studies (Meng et al., 2015; Zhang et al., 2015, 2017a; 2018b), new requirements coefficient matrices in which only domestic goods are included can be derived as,

$$A^d = (I - M)A \tag{2}$$

$$m_{ii} = \frac{X_i^m}{X_i + X_i^m - f_i^e} \tag{3}$$

where A^d is the direct requirement coefficient matrix of domestic production coefficients; I is the identity matrix; and $M = diag(m_{ii})$, m_{ii} is the share of imports in the supply of products and services to each sector.

The new balance equations are as follows,

$$X = Z^d + y^d = Z^d + f^d + f^e = A^d X + f^d + f^e \tag{4}$$

where Z^d is the matrix of domestic intermediate demands; y^d is the vector of final demand excluding imports for final consumption; f^d represents the vector of domestic final consumption; and $f^e$is the vector of domestic exports.

Then Eq. (4) can be derived as,

$$X = \left(I - A^d\right)^{-1}\left(f^d + f^e\right) = L^d\left(f^d + f^e\right) \tag{5}$$

where I is the identity matrix; and $L^d = (I - A^d)^{-1}$ is the domestic Leontief inverse matrix.

The major resource inputs into China's society include crops, forestry, rangeland, aquatic products, coal, crude oil & natural gas, ferrous metal ores, nonferrous metal ores, nonmetal minerals and other primary energy (see Table 1). For the avoidance of repetitive calculations, the entrance boundary of resource exergy inflows is set at the same level (Zhang et al., 2018a). Only chemical exergy is considered for the resource accounting in this study. Detailed