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Linkage analysis for water-carbon nexus in China

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HIGHLIGHTS

- The linkage analysis is used to investigate the water-carbon nexus in China.
- Important regions as water-carbon nexus nodes are identified.
- Outsourcing of resources and emission for stringent environmental target is suggested.

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ABSTRACT

The shortage of water resources and threat of climate change are two major global problems associated with economic development. One vital issue is to coordinate water resource utilization and CO_2 mitigation considering their coupling mechanism in socio-economic systems. This study employed linkage analysis based on a multi-regional input-output database to identify the roles of economic sector and pathway with respect to water resource utilization and CO_2 emissions, and to characterize each sector along the entire supply chain. A case study was conducted to address the status of coupled water and CO_2 in China. The results showed that Hebei, Shandong, and Inner Mongolia provinces are the major water-carbon nexus nodes for net forward linkage (net exports), i.e., mainly exporting products, embodied with large amounts of scarce water and CO_2 emissions, to fulfill the demands of other economic sectors. Guangdong, Zhejiang, Shandong, Jiangsu, and Shanghai were found to be the major water-carbon nexus for net backward linkage (net imports), i.e., mainly importing products, embodied with large amounts of scarce water and CO_2 emissions, from other sectors to meet their requirements. It can be concluded that exporter nodes are under severe water stress and have stringent CO_2 emission reduction targets, while importer nodes might transfer water stress and CO_2 emissions to the other regions via the supply chain.

1. Introduction

Water and CO_2 associated with anthropogenic production activities are intertwined within the socio-economic network, and the spillover effects between different regions make the water-carbon nexus a complex issue [1–4]. These two elements are considered coupled instead of independently because a single target policy for water or CO_2 might intrinsically influence the other via the supply chain and regional trading activities [5–7]. In addition to the nexus between water resources and CO_2 emissions, the characteristics of water stress and CO_2 reduction targets in different regions should also be considered [8]. For example, regions with serious water stress conditions and stringent CO_2 emission reduction requirements might spill over into other regions with moderate water stress conditions and lower environmental standards [9,10]. Therefore, nationally, the water-carbon nexus should be shaped with consideration of the linkages over the supply chain and the spillover effects among different regions for rational policy formulation.

The water-carbon nexus has been evaluated on specific production levels, e.g., in terms of the electricity production process and the water production process, via the methods of life cycle analysis (LCA), hybrid LCA, and material flow analysis [1,3,7,11–13]. Venkatesh et al. [1] used LCA to quantify product inflows and outflows when investigating the water-energy-carbon nexus in the water supply and sanitation systems of four cities. Stokes et al. [2] evaluated the economic benefits of the technology for the reduction of greenhouse gas emissions in terms of the potential conservation of water and energy resources via a bottom-up approach, i.e., process-based and economic input-output (IO) analysis-based LCA. Dodder et al. [3] investigated the effects of low-carbon electricity generation operations on water withdrawals or consumption with consideration of the water-carbon trade-offs throughout all life cycle stages. Li et al. [5] adopted hybrid IO-based LCA to analyze CO_2 emissions and water consumption related to wind power generation in China. They showed that wind power generation could reap double benefits, i.e., CO_2 emission reductions and water

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conservation when increasing the share of wind power. Zhang et al. [7] established two multiple linear regression models to measure the additional energy consumption and water-saving effects of a coal powered generation plant with air-cooling equipment compared to one with a wet cooling system. Laurenzi et al. [11] conducted LCA to evaluate the freshwater consumption and greenhouse gas emissions correlated with Bakken tight oil. Xin et al. [13] also used hybrid LCA to assess the impacts of electricity production on water quantity and quality as well as on CO_2 emissions. This bottom-up approach is suitable for reflecting the balance between water consumption and CO_2 emissions for a specific production activity; however, at the regional level, it would be inadequate for evaluating the linkages and spillover effects between regions with respect to the water-carbon nexus [4,14,15]. Although there have been some advances regarding the water-carbon nexus in terms of intermediate production processes, further exploration on the national level is required, especially regarding the interaction between paired regions [14,16].

Top-down approaches can explore the interactions among different regions from a more comprehensive perspective than bottom-up approaches because they track flows through both direct and indirect pathways, reflecting the influence of final demand driving on the water-carbon nexus [5,17,18]. Multi-regional input-output (MRIO) analysis is a typical top-down method used for the evaluation of resources or of the transfer of pollution within an economic transaction network [19,20]. It can demonstrate not only the dependence of different regions but also the pressure on resources or pollution transfer from both production and consumption perspectives, which facilitates explanation of the connection between paired regions with respect to certain environmental factors [21,22]. MRIO, extended with environmental coefficients, has been used widely for evaluations of water consumption, energy utilization, and CO_2 emissions on regional, national, and global levels [18,20,21,23–25]. Linkage analysis, derived from IO analysis, is able to assess the position of a certain sector or region within an economic system with regard to the total imports or exports during the entire production process [26,27]. It mainly includes forward linkages (exports) and backward linkages (imports) in the explanation of the role of a certain sector or region within the larger picture of an economic system, and it reflects the direction and effects of resource or pollution outsourcing from affluent regions [4,28].

China is facing a serious condition of imbalanced water resource distribution, and the North Water Transfer Project has been implemented for the redistribution of water resources in an attempt to alleviate water scarcity in Northern China [23]. In relation to CO_2 emissions, China contracted in the Paris Agreement to the obligation to lower its carbon intensity by 60–65% compared with the 2005 level and to reach peak CO_2 emissions by 2030 [29]. Thus, China has enacted detailed CO_2 reduction targets for different regions with consideration of their economic development conditions and reduction pressures [30], and it has established a carbon market in developed areas [31]. Therefore, to avoid unintended effects on other environmental indicators and to realize co-benefits and the balance of these two vital factors, integrated understanding of the water-carbon nexus among the regions of China is essential for developing structured policies related to water and carbon issues.

Most recent studies have evaluated the influences of economic trade activities in terms of virtual water, energy, and carbon embodied in intermediate products and final consumption. However, few studies have considered the responsibility for the water-carbon nexus transferred to the wider economy once products are exported from one region to its trading partners, i.e., the water-carbon nexus balance between the imports and exports of a region and its trading partners is ignored. To address this important research gap, this study used linkage analysis to explore the water-carbon nexus in terms of the imports, exports, and final demands of each region, i.e., the responsibilities for water consumption and CO_2 emissions from both production and consumption perspectives were decomposed. Regional disparities of water stress and carbon reduction pressure were also examined to illustrate the inequalities among and within the various regions of China.

The remainder of this paper is arranged as follows. Section 2 presents the methods adopted and a case description, i.e., the combination of MRIO with linkage analysis and basic environmental information of China's 30 regions. Section 3 illustrates the results of the investigation of the water-carbon nexus in China's 30 regions, such as the calculations of net forward linkage and net backward linkage in terms of the water-carbon nexus. Sections 4 and 5 present discussions and conclusions, respectively, based on a range of modeled results.

2. Methods and data

2.1. MRIO

The MRIO approach is to model environmental impacts with consideration both of the entire supply chain and of the pollution and resource consumption at each production stage [32], which can illustrate the interrelationships of various sectors within an economy and reveal the outsourcing effects of interregional trade [9,10]. The Leontief inverse matrix can depict the direct and indirect consumption flows driven by the total final demand, and analyze the spillover effects on resource or pollution transfer from affluent regions to less developed areas via tracking the emission/resource distribution through supply chains [23].

The basic MRIO model can be described as:

$$X = Z + Y, \tag{1}$$

where X is the total input or output, Z is the intermediate flow, and Y is the final demand. A^{rs} is defined as the technical coefficient submatrix:

$$A^{rs} = (a_{ij}^{rs}) = \left(\frac{z_{ij}^{rs}}{x_j^s}\right) \tag{2}$$

where z_{ij}^{rs} is the cross-sectoral monetary flow (i and j represent sectors, and r and s represent regions) from sector i in region r to sector j in region s, and x_j^s is the total input of sector j in region s. A^{rs} is an intermediate consumption matrix. Therefore, the MRIO evaluation can be expressed as

$$x = Ax + Y \tag{3}$$

and

$$x = (I{-}A)^{-1}Y \tag{4}$$

where $(I{-}A)^{-1}$ is the Leontief inverse matrix, showing the integrated inputs (covering direct and indirect products) required to fulfill one unit of final demand, and I stands for the identity matrix with the same scale as matrix A. Moreover, an environmental extended MRIO model associated with emissions or resources in each region (P_r) can be calculated as:

$$P_r = k_r(I{-}A)^{-1}Y^r \tag{5}$$

where P_r represents total emissions or resource consumption needed to satisfy the requirements of the production of goods and services throughout the entire supply chain driven directly and indirectly by the final demands, and k_r is a coefficient vector of resource or emissions consumption per unit of economic output in different economic sectors in region r.

2.2. Linkage analysis

Linkage analysis has been modified as the Hypothetical Extraction Method, which extracts a specific sector from the entire economic system and then assesses the role of that economic sector in terms of the integrated imports or exports [26,27]. It includes four elements of influence: the internal effect (IE), mixed effect (ME), net or external backward linkage (NBL), and net or external forward linkage (NEL).