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Interregional carbon flows of China

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HIGHLIGHTS

- The input–output model and ecological network analysis (ENA) are integrated.
- The control and dependence conditions of economic sectors in China are analyzed.
- The key regions and sectors for carbon mitigation of China are identified.

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ABSTRACT

In this paper, multi-regional input–output analysis (MRIO) and ecological network analysis (ENA) are combined to assess carbon flows within China and identify key regions and sectors in the context of spatial heterogeneity for effective carbon mitigation. An interregional carbon network model is established by articulating the directions and magnitudes of carbon flows based on MRIO. ENA is then used to unveil indirect carbon flows and mutual relationships among regions. The results show that the northwest is the largest controller for most regions in China. Most carbon emissions in the rest of China are induced by the east's final demand and substantial consumption. In addition, at sectoral level, the control and dependence abilities vary by region in China. This study provides an integrated framework to investigate interregional carbon emission structure, identify efficient pathways for coordinated emission mitigation, and reduce global carbon inequality across regions.

1. Introduction

As the major contributor to climate change, carbon emissions diffuse physically and virtually across boundaries, in which the emission is "transferred" between regions with embodiment in the trade network of products and services (i.e., CO_2 embodied in supply chains) [1–3]. It is clear that the impact of local CO_2 emissions goes far beyond territorial boundaries [4,5]. Thus, study of the carbon transfer across regions helps to understand how interregional economic activities influence carbon emission intensity [6]. Meanwhile, it has been reported that poverty mitigation by increasing income will aggravate carbon inequality and make global targets for mitigating carbon more difficult to achieve. Carbon inequality between regions induced by income differences and regional consumption patterns would thereby inform economy development and multi-region carbon mitigation objectives. Spatial heterogeneity and carbon regional inequalities must enter the climate discourse to a greater extent [7,8]. As the world's largest emitter, China has committed to cutting its carbon emissions per unit GDP by 60–65% by 2030 over 2005 levels, increase non-fossil fuel sources in primary energy consumption to about 20 percent, and reach maximum carbon emissions by 2030 per the 2015 Paris Agreement on climate change. Regional inequities of resource allocation and economic policies have made the coastal provinces pioneers in the Chinese economy, and the northern regions the leaders in the country's production industry. Because the production industry is the largest contributor to carbon emissions, many studies have focused on decreasing production or increasing the energy efficiency of specific industries [9–11], which would inevitably influence regional economic growth. In the context of economic development and carbon mitigation tasks, a new perspective is necessary to identify key regions and industries as drivers of carbon emissions and carbon inequality in China because of a disparity of actual emissions between areas of consumption and those of

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Nomenclature

IOA	input-output analysis
MRIO	multi-regional input–output
ENA	ecological network analysis
NCA	network control analysis
LCA	life cycle analysis
MFA	material flow analysis
E_i^k	total amount of energy consumed by the ith sector
h^k	heat value of the kth energy type
w^k	carbon emission factor of the kth energy type
C_i	total carbon dioxide emission related to energy consumed in the ith sector
C_{total}	total direct carbon emissions from the one city or province.
$\mathbf{O} = [o_1 \ o_2 \ \cdots \ o_n]^T$	total output vector of all sectors in one region
$\mathbf{A}$	direct requirement coefficient matrix
$\mathbf{Y} = [y_1 \ y_2 \ \cdots \ y_n]^T$	final demand vector
$\mathbf{k} = [k_1 \ k_2 \ \cdots \ k_n]^T$	carbon emission intensity vector
$f_{i,j}$	carbon flow from the jth component to the ith component
y_j	output of the jth component
z_i	input to the ith component
T_i^{in} and T_j^{out}	total flows into or out of a component
$g_{i,j} = f_{i,j}/T_j$	nondimensional, output-oriented flow
$g'_{i,j} = f_{i,j}/T_i$	nondimensional, input-oriented flow
G	output-oriented flow matrix
G'	input-oriented flow matrix
N	dimensionless integral output flow matrix
N'	dimensionless integral input flow matrix
$d_{i,j}$	direct utility of net interflow from the jth component to the ith component
$D = [d_{i,j}]$	dimensionless direct utility matrix
$CA = [ca_{i,j}]$	control allocation matrix
$DA = [da_{i,j}]$	dependence allocation matrix
CI	control index
DI	dependence index

production. Through addressing the key regions and spatial contributions of China's carbon emission network, practical government-oriented mitigation policies and market-based tools [12–14] can be further deployed in key regions and dominant sectors.

To map pathways of carbon emission "transferred" between regions with embodiment in the trade network of products and services, environmental input–output analysis (IOA) was used. IOA is based on the assumption that imported goods and services from the rest of the world (either domestic or foreign) have the same embodied energy intensity as local products, and traditional primary factors of economic production labor and capital are independent and free from indirect energy costs [15,16]. It has been widely used to analyze macroeconomic activities since Leontief's pioneering work [17–19] by integrating monetary flows and energy and material flows in economic activities into a consistent network and capturing the characteristics of both economic transactions and environmental impacts, such as environment pollution [19], ecological footprints [20,21], and material flows [22,23]. Parallel to IOA, there are bottom-up methods to investigate carbon emission impacts. For example, life cycle analysis (LCA) is a mature method to analyze the environmental impact of a product or service within its entire life cycle, based on detailed production and emission data [24,25]. Material flow analysis (MFA) can also be used to explore carbon metabolism involving technical and socioeconomic processes within countries [26,27]. Both are powerful tools for tracking carbon flows and indexing the emission intensity of economic sectors from a production perspective. This is different from IOA, which is driven by the final-demand pattern that must be justified to better interpret the national carbon profile.

In recent decades, IOA has been widely used in assessing carbon emissions "embodied" in the domestic supply chain at various scales [28–31], such as cities [32,33] and countries [34–38]. Through this, the shortcomings of current CO_2 emission assessment methods are revealed [39,40]. When embodied carbon traverses a system boundary through products or service trade, multiregional input–output analysis (MRIO) can be used to assess the impact of carbon emission in interregional socioeconomic systems. MRIO as an extension of IOA and is an appropriate method to integrate carbon emission and economic activities for demonstrating how carbon trade among regions is triggered by intermediate trade and final demand. This is done by modeling an embodied carbon network across regions in a consistent framework from an interactive perspective, as has been addressed in previous studies [41–47].

Ecological network analysis (ENA) is a system-oriented method evolved from IOA, and is often used in examining the structure of material flows in ecosystems [48–52]. Assuming that a system can be universally represented as a network of nodes (e.g., compartments or components), their connections (e.g., arcs, links, or flows) and boundary inputs and outputs have been applied not only to specific ecosystems [49–52] but to large-scale complex systems [53–56], thereby evaluating carbon emissions in cities and determining inter-sector relationships in urban metabolic processes [16,57]. The indirect effect in ENA is different from that in IOA because integral flows are used to quantify relationships between economic sectors from a systems perspective. The "control ability", determined by combination of the input/output environs of sectors, has proven useful in identifying which sectors have a more dominant role than others [43].

A few attempts have been made to combine the merits of MRIO and ENA in tracking carbon emissions (both production and consumption) [16], which shows great potential for addressing carbon flow structure between regions and explaining how carbon emissions circulate in interregional economic activities. In this paper, MRIO and ENA are integrated to analyze embodied carbon emissions and identify key sectors in seven regions of China. It is assumed that the environmental impact of carbon emissions has a linear relationship with economic output in a specific sector with a steady state [18] and conservation principle [29]. Here, the IO table and carbon emissions were combined with three aspects: 1. Transactions between sectors, implying the technology or production pattern underlying the economic system; 2. final consumption by subject (household, government or outside region, implying the consumption patterns); 3. carbon emission inventory, indicating direct environmental impacts of production behavior in the economic system, with the assumption that the carbon emission of one sector has a linear relationship with its production (i.e., the more products they produce, the more carbon they emit). Moreover, resource availability influences production cost and thus transaction activities, which is included in the economic transaction part of IO. Thus, based on MRIO and ENA, the inventory of direct carbon emissions and interregional carbon networks is developed. After tracking the dominant flows and pathways of carbon networks, policy suggestions are advanced to alleviate the potential impacts of interregional carbon emissions in China.

2. Materials and methods

2.1. Inventory of direct carbon emissions

The administrative boundary of the investigated region is defined as the system boundary of direct carbon emission accounting. A full inventory of regionally related energy flows (energy import, consumption, and export) within the system boundary is used to quantify direct