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Unveiling the Intrinsic Linkages Between "Water–Carbon–Ecology" Footprints in the Yangtze River Economic Belt and the Yellow River Basin

Daiwei Zhang [1,2,3,4,*], Ming Jing [1,2,3,4], Weiwei Chen [1,2,3,4], Buhui Chang [1,2,3,4], Ting Li [1,2,3,4], Shuai Zhang [1,2,3,4], En Liu [1,2,3,4], Ziming Li [1,2,3,4] and Chang Liu [1,2,3,4]

[1] Yellow River Institute of Hydraulic Research, Zhengzhou 450003, China; jingming1023@163.com (M.J.); chenwei0217@126.com (W.C.); changbuhui@163.com (B.C.); desertskies@126.com (T.L.); zhangqshuai@163.com (S.Z.); liuen@hhu.edu.cn (E.L.); lzm7512523@163.com (Z.L.); liuchanghhu@163.com (C.L.)
[2] Yellow River Laboratory, Zhengzhou 450003, China
[3] Henan Engineering Research Center of Rural Water Environment Improvement, Zhengzhou 450003, China
[4] Henan Key Laboratory of YB Ecological Protection and Restoration, Zhengzhou 450003, China
* Correspondence: zhangdaiwei1994@163.com

Abstract

Unveiling the relationship between the "Water–Carbon–Ecology" (W-C-E) footprints embodied in regional trade and resource flows is crucial for enhancing the synergistic benefits between economic development and environmental protection. This study constructs an association framework based on the Multi-Regional Input–Output (MRIO) model to systematically evaluate the "W-C-E" footprints and resource flow characteristics of the Yangtze River Economic Belt and the Yellow River Basin. By integrating import and export trade data, this study reveals the patterns of resource flows within and outside these regions. This research delineates the connection patterns between the "W-C-E" footprints and resource flows across three dimensions: spatial, sectoral, and environmental–economic factors. The results indicate that the Yangtze River Economic Belt has gained significant economic benefits from regional trade but also bears substantial environmental costs. Import and export trade further exacerbate the imbalance in regional resource flows, with the Yangtze River Economic Belt exporting many embodied resources through high-energy-consuming products, while the Yellow River Basin increases resource input by importing products such as food and tobacco. Sectoral analysis reveals that agriculture, electricity and water supply, and mining are the sectors with the highest net output of "W-C-E" footprints in both regions, whereas services, food and tobacco, and construction are the sectors with the highest net input. The comprehensive framework of this study can be extended to the analysis of resource–environment–economic systems in other regions, providing methodological support for depicting complex human–land system linkage patterns.

Keywords: Yangtze Economic Belt; Yellow River basin; "W-C-E" footprints; MRIO; input–output

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1. Introduction

With the escalating challenges of global climate change and resource scarcity, research on regional resource consumption and environmental impacts has emerged as a critical issue in the field of sustainable development. As two of China's most significant economic regions, the Yangtze River Economic Belt (YREB) and the Yellow River Basin (YRB) exhibit

distinct regional characteristics and strategic importance in terms of economic development, resource utilization, and environmental protection. The YREB, characterized by its high level of industrialization and urbanization, serves as a vital engine for China's economic growth. However, its rapid economic expansion has also led to substantial resource consumption and environmental impacts. Meanwhile, the YRB, as a crucial agricultural production base and ecological barrier in China, faces prominent challenges related to water scarcity and ecological fragility.

Current research has predominantly focused on the relationships between water resource utilization, energy consumption, and carbon emissions, with limited systematic comparative studies on the "W-C-E" footprints of the YREB and YRB. Ref. [1] developed a linkage framework based on the multi-regional input–output model to analyze the embodied water–energy–carbon flows and value-added transfers across 9 provinces in the Yangtze River Delta and 31 provinces nationwide in 2017, comparing these with data from 2012 and 2015. Ref. [2] employed MRIO analysis to investigate the inter-connections between water use, energy consumption, and carbon emissions in China, providing a comprehensive discussion of the water–energy–carbon nexus by considering resource utilization, carbon emissions, and inter-provincial trade and consumption activities. Ref. [3] compiled a multi-regional nested input–output table to study city-level carbon footprints and inter-regional CO_2 transfers associated with the domestic and international trade of manufactured goods across 29 cities in the Central Plains urban agglomeration. The core difference between the W-C-E framework and the W-E-C relationship lies in the focus and core elements. W-E-C focuses on the technical resource correlations of water, energy consumption and carbon emissions in human activities. W-C-E places the natural ecosystem at the core, emphasizing the inherent biophysical connections and bidirectional interactions among the water cycle, carbon cycle and ecosystem health.

To address the existing research gaps, this study focuses on the YREB and the YRB. By analyzing inter-sectoral flows, import-export trade volumes, and net output–input quantities of "W-C-E" footprints in these regions, this research aims to reveal differences in regional resource consumption and environmental impacts, as well as their underlying driving mechanisms. The findings are expected to provide a scientific basis and policy recommendations for promoting regional sustainable development.

2. Materials and Methods

2.1. Data Source

The multi-regional input–output tables for the Beijing–Tianjin–Hebei region are derived from the "Interregional Input-Output Tables of 31 Provinces, Autonomous Regions, and Municipalities in China with 42 Sectors." In this study, the 42 industrial sectors in the tables are aggregated into 13 categories, including agriculture (01), mining and quarrying (02–05), food and tobacco (06), textiles and apparel (07–08), wood processing (09), papermaking and printing (10), petroleum and chemical industries (11–12), metals and non-metals (13–15), equipment and machinery manufacturing (16–21), other manufacturing (22–24), electricity and water supply (25–27), construction (28), and services (29–42) (the numbers following the industrial sectors correspond to the sector codes in the input–output tables) [4–6].

The statistical data required for this study primarily include water usage data by sector, agricultural production data, energy data, and socio-economic data, which are mainly sourced from the Economic Census Data of the National Bureau of Statistics (stats.gov.cn), the National Bureau of Statistics, the CEAD's China Carbon Emission Accounts and Datasets (CARBON EMISSION ACCOUNTS AND DATASETS FOR EMERGING ECONOMIES), and provincial statistical yearbooks.

2.2. Calculation Model

The input–output table is a powerful tool for analyzing resource flows and environmental impacts among sectors in an economic system [7]. By integrating water consumption and carbon emission data, it can calculate the direct and indirect water and carbon footprints of various sectors, tracing their flow paths throughout the economic system [8,9]. This method involves constructing an extended input–output table and combining it with the Leontief inverse matrix to quantify the total impact of resource consumption and emissions, providing a scientific basis for water resource management, carbon reduction, and sustainable development [10–12]. This MRIO framework has cross-regional application potential, and its methodological design of coupling the "water–carbon–ecology" footprint with trade flows can be extended to different regions. Successful transplantation requires the simultaneous completion of three adaptations—calibrating environmental parameters based on the industrial characteristics of the target area, nesting local resource management policies, and focusing on typical scenarios of industrialization and resource constraints. In the future, through the development of open-source parameter toolkits and multi-regional case studies, the standardized application and verification of the framework will be systematically promoted. The application of the MRIO model in this study relies on the following core assumptions: (1) departmental homogeneity: all production activities within the same department have the same input structure and technical coefficients, and (2) technical stability: the MRIO table used represents the technical and economic structure among regions during the study period.

The input–output model can be expressed as

$$X^* = Z^* + Y^* \tag{1}$$

where X*, Z* and Y* are the total output matrix, the intermediate use matrix and the final consumption matrix, respectively. Then, the direct consumption coefficient can be calculated as

$$A^* = [A^{rs}] \tag{2}$$

$$A^{rs} = \left[\frac{z_{ij}^{rs}}{X_j^s}\right] \tag{3}$$

where A* is the intermediate use coefficient matrix; Z_{ij}^{rs} is an intermediate use from sector I of zone r to sector j of zone s; and X_j^s is the output of sector j in region s. Then the input–output model can be expressed as

$$X^* = A^* X^* + Y^* \tag{4}$$

$$X^* = (I - A^*)^{-1} Y^* \tag{5}$$

The "W-C-E" direct consumption coefficient (e_j^r) is the water, carbon and ecology produced per unit product, and the calculation formula is as follows:

$$e_j^r = \left[\frac{w_j^r}{x_j^r}\right] \tag{6}$$

$$E^r = \left[e_j^r\right] \tag{7}$$

where E^r is the W-C-E direct consumption coefficient vector of region r; w_j^r is the water/energy consumption and carbon emissions of sector j in region r; and x_j^r is the total output of sector j in region r.

Direct W-C-E consumption (E^*) can be written as

$$E^* = \begin{bmatrix} E^1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & E^n \end{bmatrix} \quad (8)$$

where n is the number of provinces in China. The "W-C-E" transfer between provinces can be written as

$$W^* = E^* X^* \quad (9)$$

It can also be written as follows:

$$W^* = E^*(I - A^*)^{-1} Y^* \quad (10)$$

where W^* is the "W-C-E" transfer matrix. The element $W^{rs} = E^r\ X_j^s$ represents the virtual "W-C-E" flow from region r to region s. Finally, the virtual "W-C-E" exchange for region r is calculated:

$$W_{export}^r = \sum_{r=1, r \neq s}^{n} W^{rs} \quad (11)$$

$$W_{import}^r = \sum_{r=1, r \neq s}^{n} W^{sr} \quad (12)$$

where W_{export}^r is the virtual "W-C-E" export of region r and W_{import}^r is the virtual "W-C-E" import of region r.

3. Results

3.1. Inter-Sectoral "W-C-E" Footprints Transfer

Figures 1 and 2 illustrate the flow of "W-C-E" footprints between sectors in the two regions. In analyzing the comparative results of inter-sectoral "W-C-E" footprint flows between the YREB and the YRB, significant sectoral differences in resource flows and environmental impacts were identified. These differences are closely related to regional industrial structures, resource endowments, and levels of economic development. The findings reveal that the sectors with the highest net output of "W-C-E" footprints in both regions are agriculture, electricity and water supply, and mining. Specifically, the net water footprint outputs of agriculture in the YREB and YRB are 608.026 billion m^3 and 574.896 billion m^3, respectively, indicating that agriculture dominates water resource consumption in both regions. This is largely due to high irrigation demands and low water-use efficiency, resulting in substantial virtual water footprints. The net carbon footprint outputs of the electricity and water supply sector are 17,394.28 Mt and 15,009.74 Mt, respectively, reflecting its significant contribution to energy consumption and carbon emissions, likely driven by reliance on fossil fuels in power generation. Notably, the ecological footprint of mining in the YRB is significantly higher than that in the YREB, potentially due to differences in mineral resource exploitation and land-use practices.

From the perspective of net input, the service sector in the YREB has the highest net water and carbon footprint inputs at 214.392 billion m^3 and 5080.33 Mt, respectively, indicating its high external dependency on resource consumption and environmental impacts. This is closely tied to the YREB's high urbanization and economic development, where sectors such as tourism, catering, and commerce demand substantial water and energy resources, particularly in densely populated urban areas. In the YRB, the food and tobacco sector have the highest net water and carbon footprint inputs at 264.085 billion m^3 and 1148.12 Mt, respectively, reflecting its significant external dependency on resources and

environmental impacts, likely due to high water and energy demands in food processing and tobacco production [13,14]. The construction sector in both regions have the highest net ecological footprint inputs, at 10.18 × 10^6 hm^2 and 704.68 × 10^6 hm^2, respectively, indicating its high external dependency on land-use and ecological resource consumption. This is particularly pronounced in the YRB, where rapid infrastructure development and urbanization have intensified ecological pressures.

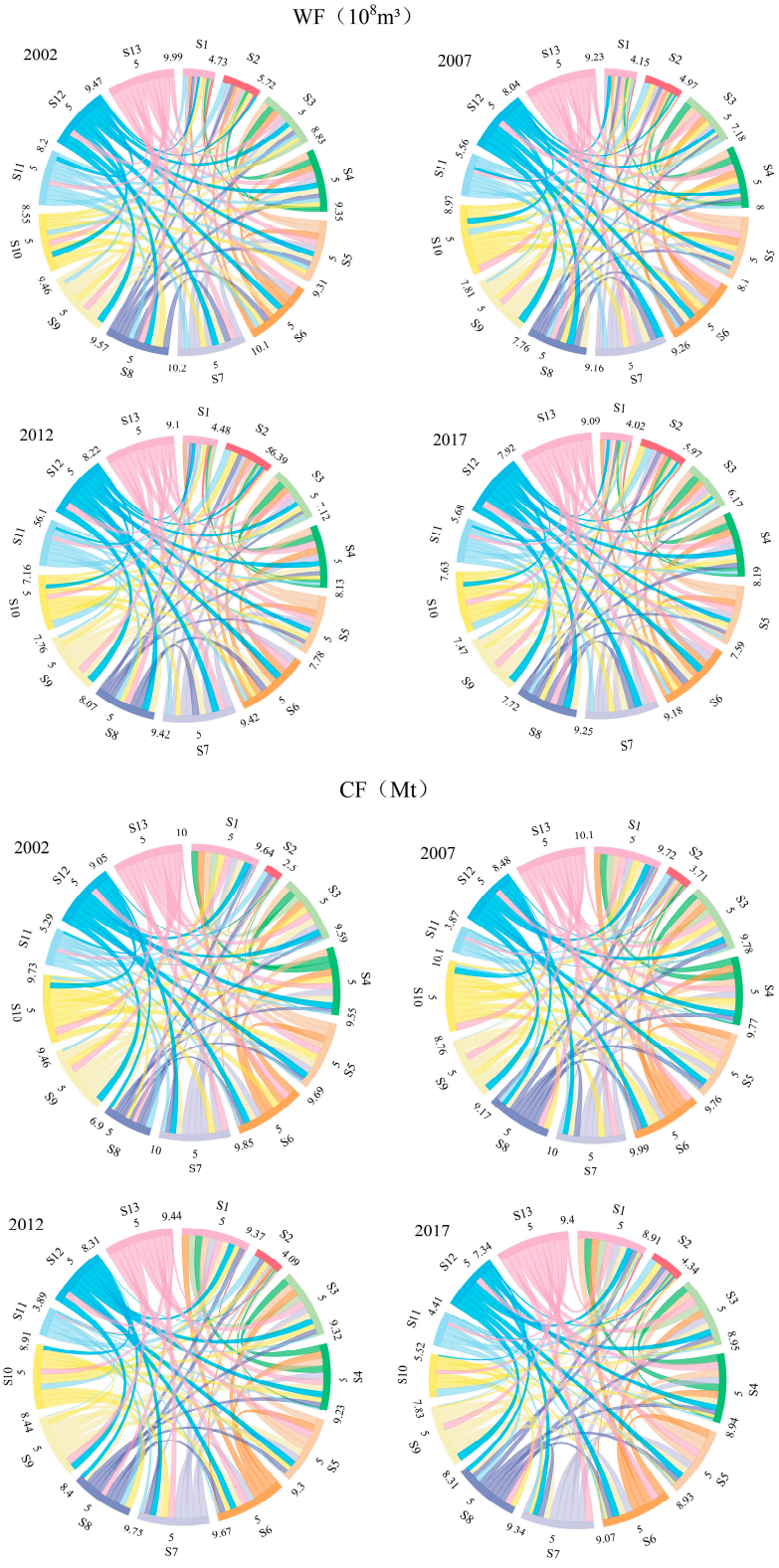


Figure 1. *Cont.*

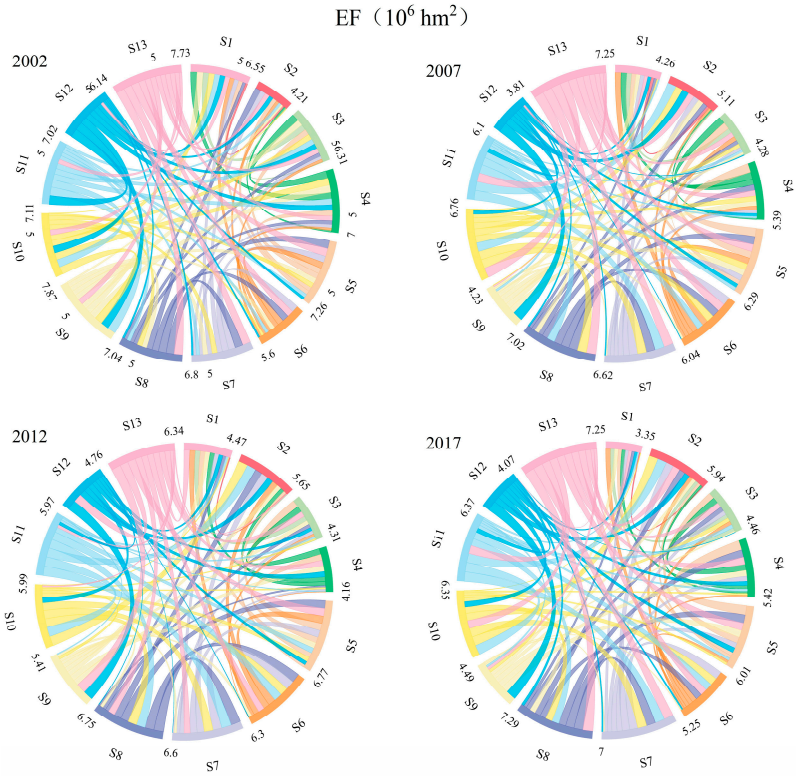


Figure 1. Inter-sectoral flows of "W-C-E" footprints in the YREB.

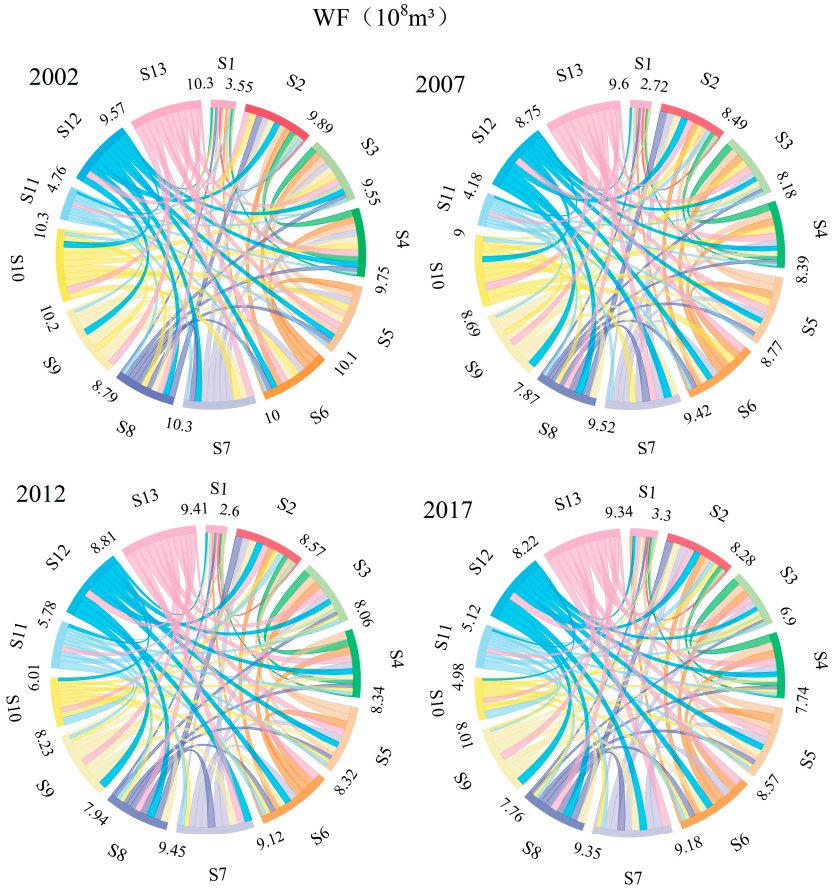


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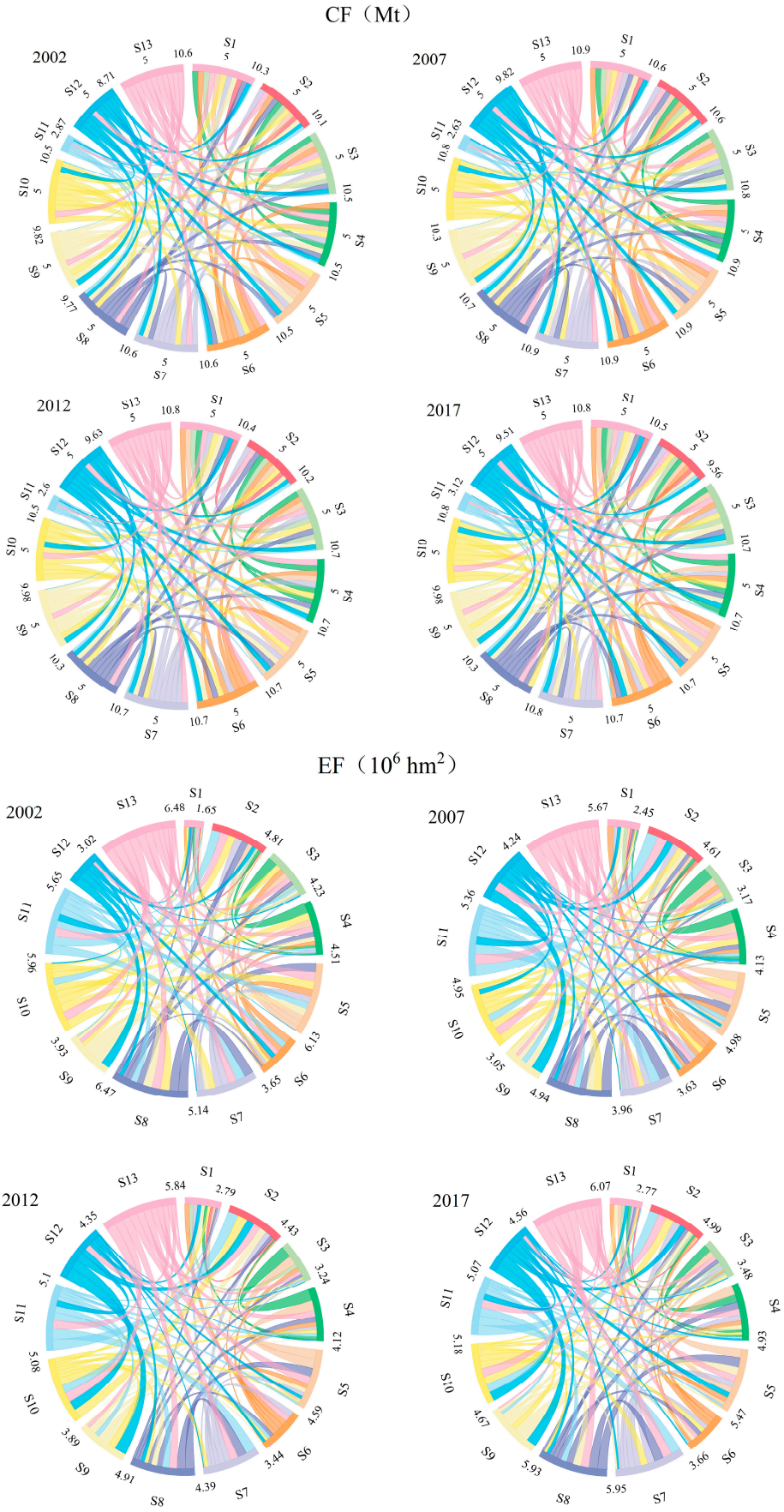


Figure 2. Inter-sectoral flows of "W-C-E" footprints in the YRB.

These inter-sectoral differences in resource flows reflect the distinct industrial structures, resource endowments, and economic development levels of the two regions. The YREB, as a key driver of China's economic growth, exhibits high demand for water and energy due to its advanced service sector, while its reliance on fossil fuels in electricity and water supply underscores significant carbon emissions [15,16]. In contrast, the dominance of agriculture and the food and tobacco sector in the YRB highlights its role as a major agricultural base, but also reveals challenges in water resource management and energy efficiency. Additionally, the significant ecological footprints of mining and construction in both regions, particularly in the YRB, underscore the environmental impacts of mineral resource exploitation and land-use practices, which may exacerbate ecological pressures [17].

From the perspective of environmental impacts and sustainable development, the high net outputs of agriculture, electricity and water supply, and mining indicate substantial externalization effects in resource consumption and environmental impacts. To achieve sustainable development, these sectors must transition toward green and low-carbon practices. For example, agriculture can adopt water-saving irrigation technologies and sustainable farming practices to reduce virtual water footprints; the electricity and water supply sector can improve energy efficiency and promote renewable energy to lower carbon emissions; and mining can enhance resource extraction technologies and strengthen ecological restoration to minimize ecological resource consumption [18–20]. Meanwhile, the high net inputs of the service, food and tobacco, and construction sectors suggest significant external dependencies, necessitating industrial structure optimization, improved resource-use efficiency, and enhanced regional collaborative governance to reduce reliance on external resources [21].

Addressing these challenges requires multifaceted policy interventions. First, promoting green and low-carbon transitions in high-resource-consumption sectors is critical. Second, optimizing industrial structures to reduce external dependencies is essential. The service, food and tobacco, and construction sectors should leverage technological innovation and management optimization to improve resource efficiency. Third, strengthening regional collaborative governance is vital. The disparities in resource flows and environmental impacts between the two regions highlight the need for cross-regional resource allocation mechanisms and environmental compensation schemes to promote efficient resource use and sustainable environmental management [22,23].

This study primarily focuses on inter-sectoral resource flow analysis and does not fully account for regional variations in resource-use efficiency, technological capabilities, and management capacities. Future research could refine inter-sectoral resource flow analyses by incorporating economic, social, and environmental factors to provide more targeted policy recommendations. Additionally, this study does not address the impact of international trade on regional "W-C-E" footprints. As globalization accelerates, the role of international trade in resource flows and environmental impacts becomes increasingly significant. Future studies should incorporate international trade factors to comprehensively assess regional resource dependencies and environmental impacts.

In conclusion, the YREB and YRB exhibit significant differences in inter-sectoral "W-C-E" footprint flows, reflecting their distinct industrial structures, resource endowments, and economic development levels. The high net outputs of agriculture, electricity and water supply, and mining reveal substantial externalization effects in resource consumption and environmental impacts, while the high net inputs of the service, food and tobacco, and construction sectors indicate significant external dependencies. To achieve sustainable development, both regions must accelerate industrial structure optimization, promote green and low-carbon transitions, and strengthen regional collaborative governance. Future research should further refine resource flow mechanisms and integrate multidimensional

factors to provide a more comprehensive scientific basis for regional resource management and environmental protection.

Figure 3 presents the inflow and outflow values between sectors in the two river basins. In summary, the high input levels of the service sector in the "W-C-E" footprints of the YREB reflect its characteristics of high urbanization and economic development, while the high input levels of the food and tobacco industry and the mining sector in the YRB underscore the dominant roles of agriculture and resource-intensive industries in the region. The high net output levels in the YREB indicate significant potential for improving resource-use efficiency, particularly in energy production and manufacturing sectors [24]. In contrast, the YRB needs to focus on enhancing agricultural irrigation efficiency and ensuring the sustainability of mineral resource exploitation.

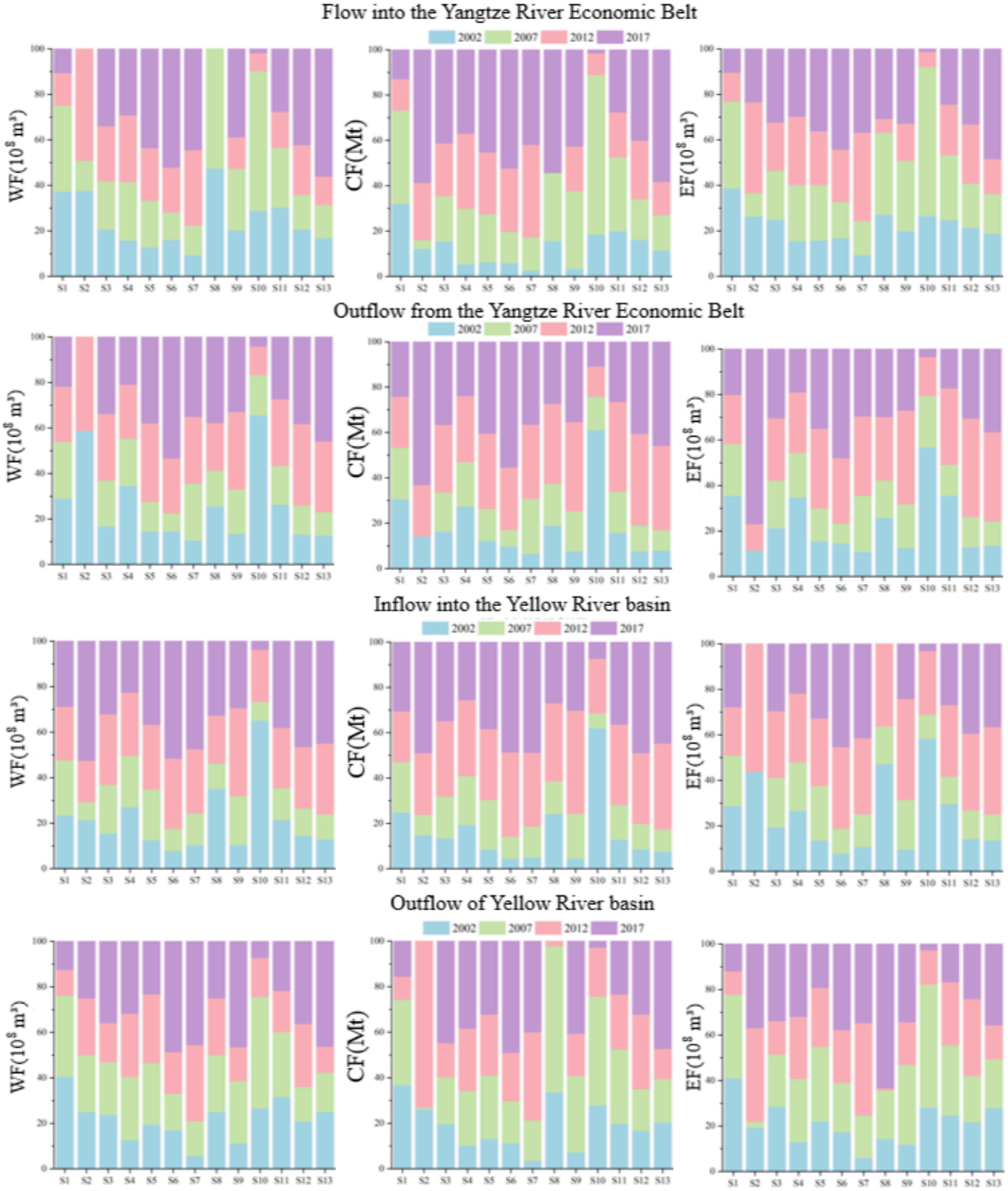


Figure 3. The inflow and outflow of funds among various sectors in the YREB and the YRB.

To achieve sustainable development, the YREB should promote the green transformation of its service sector, reduce its dependency on water and energy resources, and optimize its energy structure to lower carbon emissions. Meanwhile, the YRB should prioritize improving agricultural irrigation efficiency to reduce virtual water footprints and strengthen ecological protection in mineral resource development [25]. Both regions must enhance collaborative governance, optimize the structure of import and export trade, and mitigate the cross-boundary transfer of resource and environmental pressures [26].

The comprehensive framework developed in this study can serve as a reference for analyzing resource–environment–economy systems in other regions, providing a scientific basis for balancing regional development and environmental protection. By addressing sector-specific challenges and fostering inter-regional cooperation, the YREB and YRB can pave the way for more sustainable and resilient development models. Future research should further refine this framework by incorporating additional dimensions such as technological innovation, policy effectiveness, and international trade dynamics to offer more holistic and actionable insights.

3.2. Transfer of "W-C-E" Footprints in Import and Export Trade

Figures 4 and 5 illustrate the flow of "W-C-E" footprints in the import and export trade of the two regions. As shown, the sectors with the highest "W-C-E" footprints trade volumes in the YREB are the service sector, equipment and machinery manufacturing, and equipment and machinery manufacturing, with net trade volumes of 6.233 billion m^3, 6124.25 Mt, and 6755.66 $\times$ 10^6 hm^2, respectively. In the YRB, the sectors with the highest trade volumes are agriculture, equipment and machinery manufacturing, and equipment and machinery manufacturing, with net trade volumes of 4.33 billion m^3, 1045.39 Mt, and 1039.03 $\times$ 10^6 hm^2, respectively. During the study period, the net trade volumes of "W-C-E" footprints in the YREB were 3.862 billion m^3, 6327.88 Mt, and 7725.28 $\times$ 10^6 hm^2, while those in the YRB were 8.838 billion m^3, 1455.97 Mt, and 1839.77 $\times$ 10^6 hm^2, respectively.

Significant differences in resource dependency and environmental impacts exist between the two regions, closely tied to their industrial structures, resource endowments, and levels of economic development. Meanwhile, the significant contribution of equipment and machinery manufacturing to the carbon and ecological footprints highlights the region's role as a major manufacturing base in China, where industrial production demands high energy and raw material inputs, leading to substantial carbon emissions and ecological resource consumption. This industrial structure results in a high dependency on external resources for both resource consumption and environmental impacts. In contrast, the dominance of agriculture in the virtual water footprint of the YRB underscores its role as a key agricultural production base in China. However, due to high irrigation demands and low water-use efficiency, the virtual water footprint remains elevated. The contribution of equipment and machinery manufacturing to the carbon and ecological footprints indicates that, despite the YRB's relatively lower level of industrialization, this sector remains a major source of resource consumption and environmental impacts in the region.

From the perspective of regional imbalances in resource flows, the differences in the net trade volumes of "W-C-E" footprints between the YREB and YRB reflect disparities in resource flows and environmental impacts. The YREB exhibits higher net inputs, particularly in carbon and ecological footprints, indicating its heavy reliance on external resources to support economic development and the associated environmental pressures. The YRB's significantly higher net input of virtual water footprints suggest a stronger dependency on water resources, potentially exposing the region to greater risks of water scarcity. These imbalances are not only related to regional industrial structures but may also be influenced by differences in economic development levels, resource endowments, and policy orienta-

tions. For instance, as one of China's most economically developed regions, the YREB's high consumption levels and production activities drive substantial resource demands, while the YRB faces greater resource pressures due to its relative water scarcity and strong agricultural dependency.

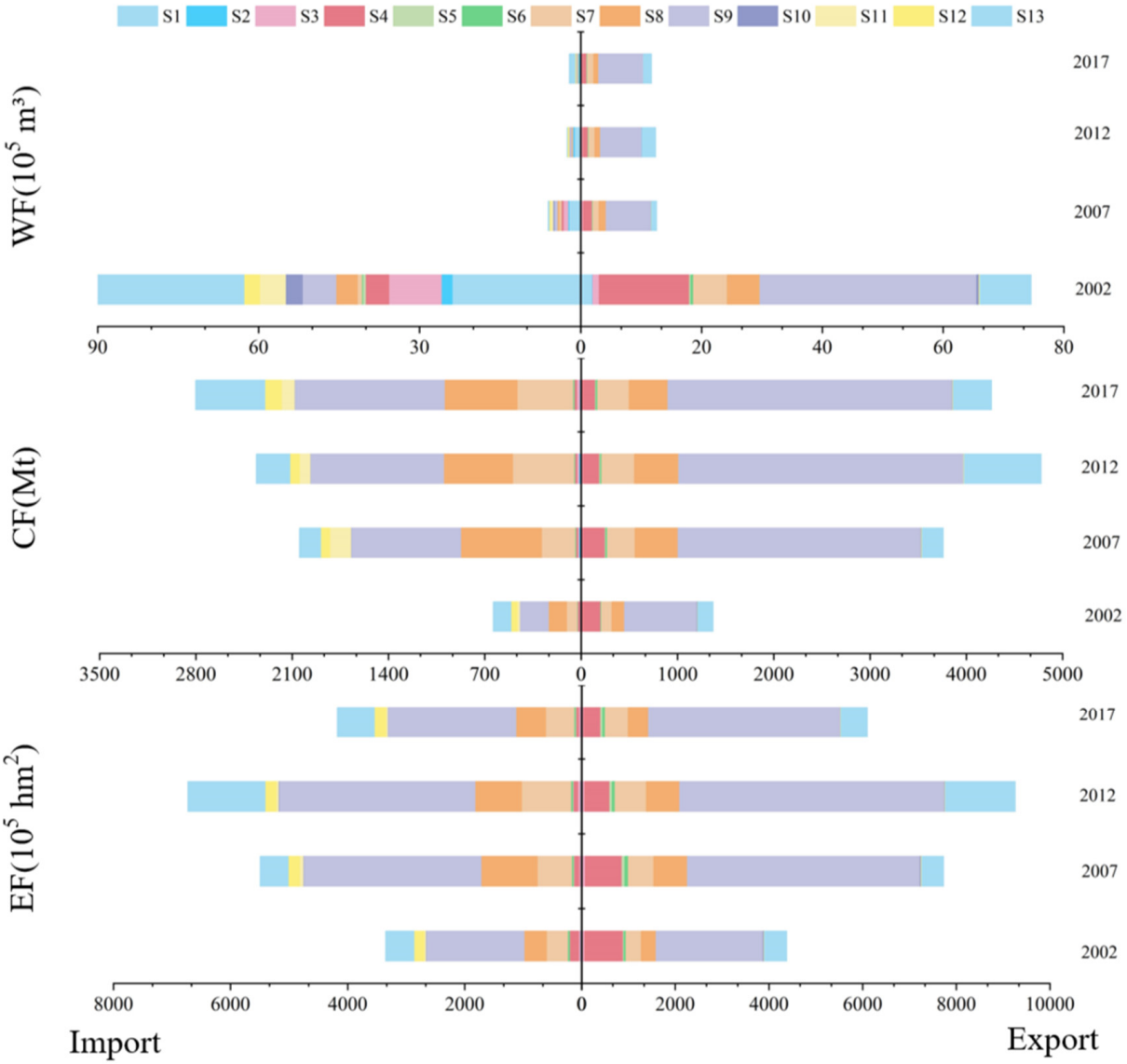


Figure 4. Flow values of "W-C-E" footprints in the import and export trade of the YREB.

In terms of environmental impacts and sustainable development, equipment and machinery manufacturing play a significant role in the carbon footprints of both regions, indicating that this sector is a major source of regional carbon emissions. This is not only related to energy structures (e.g., coal dependency) but may also be constrained by production technologies and management practices. To achieve carbon reduction goals, promoting the green transformation of this sector is crucial. Additionally, the high net inputs of ecological footprints suggest that both regions consume substantial land, forest, and other ecological resources during economic development, potentially leading to ecosystem degradation and biodiversity loss. This is particularly evident in the YREB, where intensive industrialization and urbanization exert significant pressure on ecosystems. The YRB's virtual water footprint issue is especially prominent, likely due to inefficient agricultural irrigation and poor water resource management. With climate change and water scarcity intensifying, the YRB may face even greater water resource pressures.

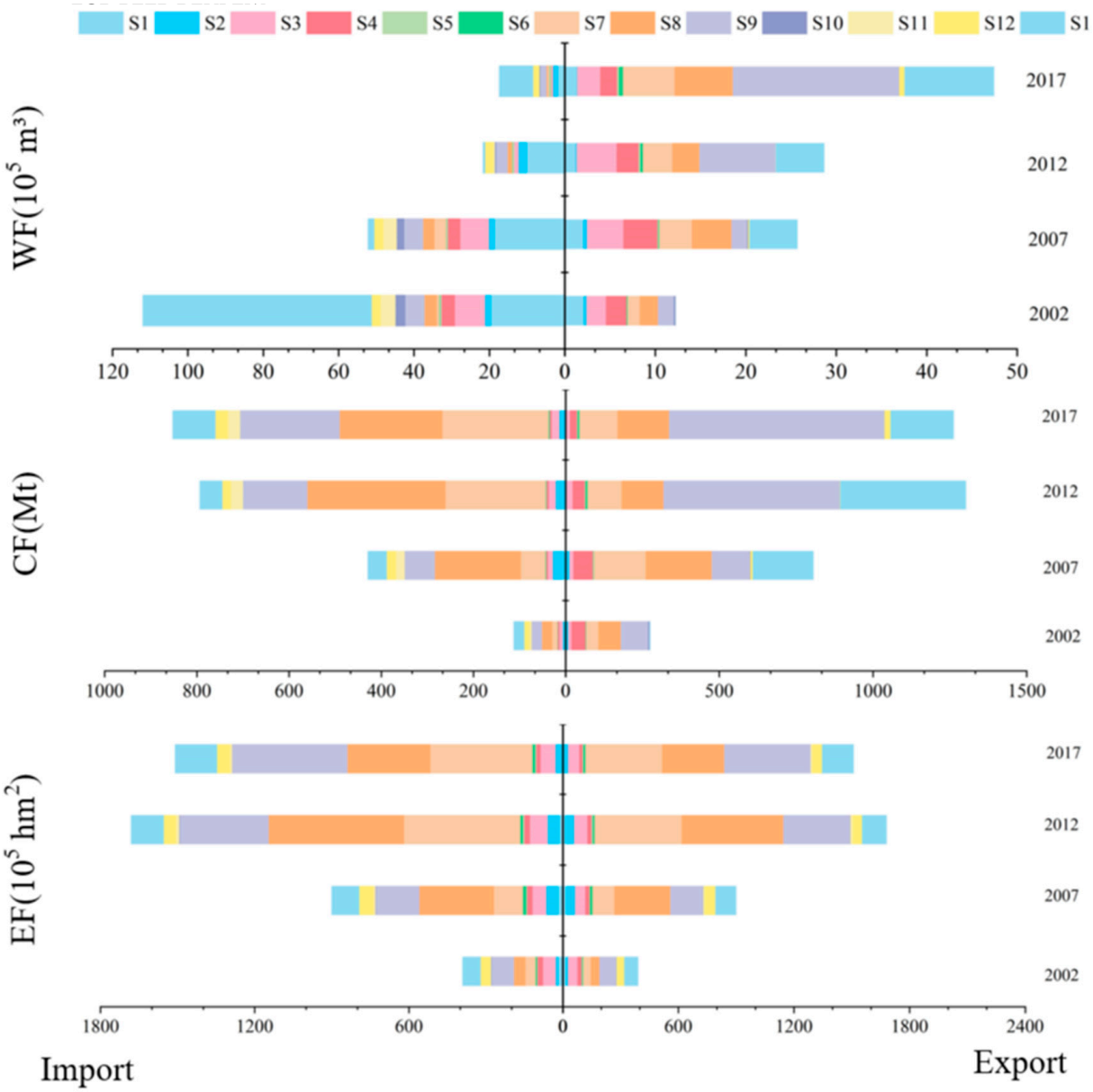


Figure 5. Flow values of "W-C-E" footprints in the import and export trade of the YRB.

This study primarily focuses on net trade volume analysis and does not fully account for regional variations in resource-use efficiency, technological capabilities, and management capacities. Future research could refine inter-sectoral resource flow analyses by incorporating economic, social, and environmental factors to provide more targeted policy recommendations. Additionally, this study does not address the impact of international trade on regional "W-C-E" footprints. As globalization accelerates, the role of international trade in resource flows and environmental impacts becomes increasingly significant. Future studies should incorporate international trade factors to comprehensively assess regional resource dependencies and environmental impacts.

To address these challenges, policy interventions must be multifaceted. First, optimizing industrial structures is critical. The YREB should promote the green transformation of its service sector to reduce excessive water dependency, while equipment and machinery manufacturing should accelerate the adoption of green manufacturing technologies to lower carbon emissions and ecological resource consumption. The YRB should improve agricultural irrigation efficiency and promote water-saving technologies to reduce virtual

water footprints. Second, strengthening regional collaborative governance is essential. The imbalances in resource flows and environmental impacts between the two regions highlight the need for cross-regional resource allocation mechanisms and environmental compensation schemes to promote efficient resource use and sustainable environmental management. Third, advancing technological innovation and policy support is vital. Clean production technologies and circular economy models should be promoted in equipment and machinery manufacturing to reduce carbon emissions and ecological resource consumption. Governments should enhance policy support for water resource management and ecological protection, such as through water pricing mechanisms and ecological compensation policies, to incentivize resource conservation and environmental protection [27]. Finally, building climate change adaptation capabilities is crucial. The YRB's water resource challenges may worsen due to climate change, necessitating improved water management infrastructure and the promotion of drought-resistant crop varieties.

In conclusion, the YREB and YRB exhibit significant sectoral differences and regional imbalances in "W-C-E" footprint trade. To achieve sustainable development, industrial structures must be optimized, regional collaborative governance strengthened, technological innovation promoted, and climate change adaptation capabilities enhanced. Future research should further refine resource flow mechanisms and integrate multidimensional factors to provide a more comprehensive scientific basis for regional resource management and environmental protection.

3.3. The Transfer of "W-C-E" Footprints Between the Two Regions

As shown, the YREB exhibit net outflows of "W-C-E" footprints, with net outflow volumes of 240.583 billion m^3, 9919.26 Mt, and 1453.81 $\times$ 10^6 hm^2, respectively. In contrast, the YRB demonstrate net inflows, with net inflow volumes of 205.491 billion m^3, 6998.72 Mt, and 1232.66 $\times$ 10^6 hm^2, respectively. These results indicate significant regional disparities and resource flows in "W-C-E" footprints between the YREB and YRB. These differences reflect the YREB's role as a key driver of China's economic development, where resource consumption and environmental impacts are substantial, and production and consumption activities exceed the region's carrying capacity for water resources, carbon emissions, and ecological resources. In contrast, the YRB's relatively lower resource consumption may be attributed to its economic development level, industrial structure, and ecological carrying capacity. The "W-C-E" footprints flow from the YREB to the YRB, with maximum net inflow volumes of 86.951 billion m^3, 3168.58 Mt, and 586.73 $\times$ 10^6 hm^2, respectively. Additionally, the "W-C-E" footprints from the YREB to other provinces exhibit net inflow values of 62.327 billion m^3, 3446.62 Mt, and 410.98 $\times$ 10^6 hm^2, respectively, while those from other provinces to the YRB show net inflow values of 24.195 billion m^3, 526.54 Mt, and 188.76 $\times$ 10^6 hm^2, respectively.

From the perspective of regional economic development levels and industrial structures, the YREB's high net outflows are closely tied to its characteristics of high industrialization and urbanization. As a critical engine of China's economic growth, the YREB hosts a concentration of manufacturing and service industries, particularly energy-intensive and high-emission sectors such as equipment and machinery manufacturing and chemical industries. These sectors demand vast amounts of water, energy, and ecological resources, leading to resource consumption and environmental impacts that exceed the region's carrying capacity [28,29]. Moreover, the YREB's high consumption levels further exacerbate the externalization of resources.

The regional disparities in resource flows also reflect differences in ecological carrying capacity and resource management capabilities between the two regions. The YREB's high net outflows indicate that the region has not fully achieved efficient resource utilization and

sustainable environmental management during its rapid economic development, leading to the externalization of resource consumption and environmental impacts. This externalization not only intensifies resource pressures within the region but may also negatively impact the environments of other regions. The YRB's net inflow status suggests that its resource consumption is relatively lower and its ecological carrying capacity stronger, but it may also face external dependencies and potential environmental risks from resource inflows (Chen et al., 2021) [26]. For instance, the net inflow of virtual water may mask internal water scarcity issues, while the net inflows of carbon and ecological footprints could exacerbate environmental pressures within the region.

In terms of environmental impacts and sustainable development, the YREB's high net outflows reveal the severe challenges it faces in resource consumption and environmental protection. To achieve sustainable development, the YREB must accelerate industrial restructuring, promote the green and low-carbon transformation of energy-intensive and high-emission industries, and strengthen resource management and environmental protection to reduce the externalization of resource consumption and environmental impacts. Although the YRB exhibits net inflows, it must remain vigilant about the potential risks associated with resource inflows. For example, the net inflow of virtual water may obscure internal water scarcity issues, while the net inflows of carbon and ecological footprints could intensify environmental pressures. Therefore, the YRB needs to enhance resource management, improve resource-use efficiency, and promote inter-regional collaborative governance to facilitate efficient resource allocation and sustainable environmental management.

Addressing these challenges requires multifaceted policy interventions. First, the YREB should accelerate industrial structure optimization, promote the green and low-carbon transformation of energy-intensive and high-emission industries, and reduce the externalization of resource consumption and environmental impacts. Simultaneously, it should strengthen resource management and environmental protection to improve resource-use efficiency and environmental governance capabilities. Second, the YRB should enhance resource management, improve resource-use efficiency, and reduce dependency on external resources. It should also promote inter-regional collaborative governance to facilitate efficient resource allocation and sustainable environmental management. Additionally, advancing technological innovation and policy support is crucial. Both regions should adopt clean production technologies and circular economy models to reduce resource consumption and environmental impacts. Governments should increase policy support for resource management and environmental protection, such as through resource pricing mechanisms and ecological compensation policies, to incentivize resource conservation and environmental protection.

This study primarily focuses on net outflow and inflow analyses and does not fully account for regional variations in resource-use efficiency, technological capabilities, and management capacities. Future research could refine inter-sectoral resource flow analyses by incorporating economic, social, and environmental factors to provide more targeted policy recommendations. Additionally, the study does not address the impact of international trade on regional "W-C-E" footprints. As globalization accelerates, the role of international trade in resource flows and environmental impacts becomes increasingly significant. Future studies should incorporate international trade factors to comprehensively assess regional resource dependencies and environmental impacts.

In conclusion, the YREB and YRB exhibit significant disparities in net outflows and inflows of "W-C-E" footprints, reflecting differences in their economic development levels, industrial structures, and ecological carrying capacities. The YREB's high net outflows reveal the severe challenges it faces in resource consumption and environmental protection, while the YRB's net inflow status indicates relatively lower resource consumption but

also highlights potential risks associated with resource inflows. To achieve sustainable development, both regions must accelerate industrial structure optimization, strengthen resource management and environmental protection, and promote inter-regional collaborative governance. Future research should further refine resource flow mechanisms and integrate multidimensional factors to provide a more comprehensive scientific basis for regional resource management and environmental protection.

4. Conclusions

This study, through an analysis of inter-sectoral flows, net outputs, and net inputs of "W-C-E" footprints in the YREB and the YRB, reveals significant differences in resource consumption and environmental impacts between the two regions, as well as the underlying driving mechanisms. The main conclusions are as follows:

1. Net outflows in the YREB and net inflows in the YRB:

The YREB exhibits net outflows of "W-C-E" footprints, with net outflow volumes of 240.583 billion m^3, 9919.26 Mt, and 1453.81 $\times$ 10^6 hm^2, respectively. This indicates that, as a critical engine of China's economic development, the YREB's resource consumption and environmental impacts exceed it carrying capacity. In contrast, the YRB shows net inflows, with net inflow volumes of 205.491 billion m^3, 6998.72 Mt, and 1232.66 $\times$ 10^6 hm^2, respectively, reflecting its relatively lower resource consumption but higher dependency on external resources. These regional disparities are closely tied to differences in economic development levels, industrial structures, and ecological carrying capacities.

2. Key sectors with high net outputs and inputs:

Agriculture, electricity and water supply, and mining are the sectors with the highest net outputs of "W-C-E" footprints in both regions. Agriculture dominates the water footprints, with net outputs of 608.026 billion m^3 and 574.896 billion m^3, respectively, highlighting the high water demand for irrigation. The electricity and water supply sector contributes significantly to carbon footprints, with net outputs of 17,394.28 Mt and 15,009.74 Mt, reflecting the substantial carbon emissions from energy production.

3. Externalization effects in the YREB and dependency in the YRB:

The YREB's high net outflows demonstrate significant externalization effects in resource consumption and environmental impacts during its rapid economic development, particularly from energy-intensive sectors such as equipment and machinery manufacturing and electricity and water supply, which contribute substantially to carbon emissions and ecological resource consumption. The YRB's net inflow status suggests a high dependency on external resources, potentially masking internal water scarcity and ecological pressures. This externalization not only intensifies resource pressures within the regions but may also negatively impact the environments of other regions. It is necessary to promote efficient water-saving irrigation (such as drip irrigation) and tiered water pricing in the YRB (especially in agriculture) to reduce the virtual water content of agricultural products; accelerate the application of renewable energy (wind/solar/hydropower) in the YREB power sector to reduce the embodied carbon of high-energy-consuming products; implement a circular economy (such as solid waste resource utilization and remanufacturing) in the YREB manufacturing industry to reduce the resource footprint; and establish a cross-regional ecological compensation mechanism based on the net flow of W-C-E calculated in this study. The YREB compensates the YRB for ecological protection and green development to promote regional equity.

4. Pathways to sustainable development:

To achieve sustainable development, the YREB must accelerate industrial restructuring, promote the green and low-carbon transformation of energy-intensive and high-emission industries, and reduce the externalization of resource consumption and environmental

impacts. The YRB should strengthen water resource management and ecological protection, improve resource-use efficiency, and reduce dependency on external resources. Both regions need to enhance inter-regional collaborative governance by establishing cross-regional resource allocation mechanisms and environmental compensation schemes to facilitate efficient resource use and sustainable environmental management.

5. Limitations and future research directions:

This study primarily focuses on net output and input analyses and does not fully account for regional variations in resource-use efficiency, technological capabilities, and management capacities. Future research could refine inter-sectoral resource flow mechanisms by incorporating economic, social, and environmental factors to provide more targeted policy recommendations. Furthermore, the impact of international trade on regional "W-C-E" footprints has not been considered. Future studies should incorporate globalization factors to comprehensively assess regional resource dependencies and environmental impacts. Future research needs to construct a dynamic multi-regional input–output model integrating refined international trade network analysis, systematically quantify the long-term mechanism of the evolution of global supply chains and technological upgrades on the flow of regional "W-C-E" footprints, and provide scientific support for formulating regional collaborative policies that adapt to globalization and technological changes.

In conclusion, the YREB and YRB exhibit significant regional disparities and inter-sectoral resource flow characteristics in "W-C-E" footprints, reflecting differences in their economic development levels, industrial structures, and ecological carrying capacities. To achieve sustainable development, both regions must optimize industrial structures, promote green transitions, strengthen inter-regional collaborative governance, and leverage technological innovation and policy support to enhance resource-use efficiency and sustainable environmental management.

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