Spatiotemporal Dynamics and Emission Reduction Potential of the Ecological Footprint of Industrial Carbon Emissions in China, 2000–2021: Postprint

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Abstract

Industry is a key sector for achieving carbon peak and carbon neutrality goals; however, existing research lacks systematic investigation into the spatiotemporal dynamic evolution of industrial carbon emission ecological footprints and their multi-scale impacts on ecosystems. Based on a three-dimensional ecological footprint model, this study calculates the industrial carbon footprint of 30 provinces (municipalities and autonomous regions) in China from 2000 to 2021, reveals its spatiotemporal dynamic evolution characteristics, and assesses regional emission reduction potential. The results indicate: (1) China' s industrial carbon footprint exhibits significant spatiotemporal disparities, reflecting differences in regional industrial structures and energy consumption patterns. The central and western regions face continuously increasing emission pressure due to undertaking high-energy-consuming industries, while the eastern region has shown improvement. (2) Carbon sink flow and stock resources exhibit complementarity among different regions, but overall imbalance exists, with carbon sink resources in some regions facing overload risks. (3) Both the breadth and depth of industrial carbon footprint demonstrate significant spatial positive correlation, and the agglomeration effect continues to strengthen over time, showing an inland, patchy, and marginalization migration trend that reveals the gradient transfer characteristics of industrial carbon emissions. (4) Significant differences exist in carbon emission reduction characteristics and potential among different regions; the eastern region possesses greater emission reduction potential, while the central and western regions need to prioritize the sustainable utilization of carbon sink resources. This study reveals the dynamic relationship between industrial carbon emissions and ecosystem carrying capacity from an ecological perspective, proposes differentiated emission reduction strategies based on regional differences, and provides a scientific basis for constructing a collabo-

rative governance model of low-carbon industrial development and ecological protection.

Full Text

Assessment of the Spatio-temporal Dynamics and Emission Reduction Potential of China's Industrial Carbon Footprint from 2000 to 2021

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Abstract

Industry represents the critical sector for achieving carbon peaking and carbon neutrality objectives, yet existing research lacks systematic investigation into the spatio-temporal dynamic evolution of industrial carbon emission ecological footprints and their multi-scale impacts on ecosystems. Based on the Three-Dimensional Ecological Footprint Model, this study calculates the industrial carbon footprint of 30 provinces (municipalities and autonomous regions) in China from 2000 to 2021, reveals its spatio-temporal dynamic evolution characteristics, and evaluates regional emission reduction potential. Key findings include: (1) China' s industrial carbon footprint exhibits significant spatio-temporal heterogeneity, reflecting regional disparities in industrial structure and energy consumption patterns. Central and western regions face mounting emission pressures due to absorbing relocated energy-intensive industries, while eastern regions show improvements. (2) Carbon sink flows and stocks demonstrate regional complementarity but overall imbalance, with some areas confronting overloading risks for carbon sequestration resources. (3) Both the size and depth of industrial carbon footprints display significant spatial positive correlation that strengthens over time, showing enhanced agglomeration effects with trends of inland migration, clustered distribution, and peripheral relocation, thereby revealing gradient transfer characteristics of industrial carbon emissions. (4) Carbon reduction features and potentials vary substantially across regions; eastern regions possess greater mitigation potential, whereas central and western regions require prioritized focus on sustainable utilization of carbon sink resources. This study reveals the dynamic relationship between industrial carbon emissions and ecosystem carrying capacity from an ecological perspective, and proposes differentiated emission reduction strategies based on regional disparities, providing a scientific basis for constructing a collaborative governance model that integrates low-carbon industrial development and ecological protection.

Keywords: industrial carbon emissions; carbon footprint; emission reduction potential; Three-Dimensional Ecological Footprint Model

Introduction

Against the backdrop of global climate change, the contradiction between industrialization and ecological protection is intensifying. Industrial carbon emissions, as the primary source of greenhouse gases, simultaneously consume substantial natural carbon sink resources such as forests and grasslands, severely undermining the carbon balance regulation capacity of ecosystems. This systematic interference with the carbon cycle not only triggers carbon sink functional degradation but also exacerbates cascading ecological crises including biodiversity loss. Against this context, quantifying the impact of industrial carbon emissions on ecosystems and establishing a scientific ecological footprint assessment system hold profound significance for coordinating human activities with ecological protection.

As the world' s largest developing country, China' s industrial carbon emissions have exerted far-reaching impacts on ecosystems through their spatio-temporal evolution. On one hand, industrial carbon emission intensity in eastern regions has gradually decreased under industrial upgrading and policy regulation, alleviating ecosystem pressure. On the other hand, central and western regions face continuously mounting industrial emission pressure due to absorbing energy-intensive industries from the east, exposing ecosystems to greater risks of carbon sink resource overload. This inter-regional carbon emission transfer not only aggravates regional development imbalances but also poses new challenges to ecosystem carbon carrying capacity.

A comprehensive review of existing literature reveals that research on industrial carbon emission ecological footprints remains scarce, particularly regarding spatio-temporal dynamic evolution and ecosystem impacts. Previous studies have focused on three main aspects: First, measurement, evaluation, and prediction, primarily examining historical industrial carbon emission accounting and assessment across different periods and regions, analyzing emission volume, intensity, and performance to provide data support for policy formulation, as well as conducting future emission projections and peaking simulations through model construction and scenario design. Second, research scales have predominantly focused on single regions or specific industries, such as individual provinces, urban agglomerations, particular industrial sectors like non-ferrous metals, papermaking, or chemical industries, making it difficult to reveal nationwide patterns and inter-regional synergies. Third, research content has thoroughly analyzed driving factors, emission scenarios, and mitigation pathways, examining economic and policy drivers, conducting precise predictions for various emission scenarios, and proposing mitigation approaches such as technological innovation and structural adjustment. Despite substantial progress, existing research still lacks systematic investigation into ecosystem impacts.

The Three-Dimensional Ecological Footprint Model offers a new perspective for quantifying regional carbon emissions. Traditional methods such as emission factor method, input-output analysis, and life cycle assessment, while widely applied, fail to reflect ecosystem impacts. The emission factor method lacks localized factors, causing distortion at micro scales; input-output analysis obscures specific emission source identification due to sectoral aggregation; life cycle assessment focuses on product chain emissions while neglecting ecosystem impacts. The Three-Dimensional Ecological Footprint Model, characterized by its integration of dynamic and static analysis, three-dimensional expression, and multi-dimensional assessment, can dynamically track spatio-temporal migration patterns of carbon emissions and their ecological impacts through the dimensions of footprint size and depth. This enables evaluation of regional industrial emission reduction potential from the perspective of industrial carbon emission loads and identification of key mitigation regions.

Therefore, this study employs the Three-Dimensional Ecological Footprint Model to calculate the industrial carbon emission ecological footprint of 30 provinces in China from 2000 to 2021, analyze its spatio-temporal evolution characteristics, and assess regional emission reduction potential. The aim is to comprehensively reveal the dynamic distribution patterns of regional industrial carbon emissions, explore differences in mitigation policy design across regions, and promote the transition of the entire industrial system toward low-carbon and high-efficiency development.

1. Data and Methods

1.1 Data Sources and Processing The research data encompass multiple dimensions to ensure comprehensive and accurate accounting of China's regional industrial carbon emission ecological footprint. The data foundation consists of the following components.

1.1.1 Energy Consumption Data

Energy consumption data were obtained from the *China Energy Statistical Yearbook* (2000-2021) and provincial statistical bulletins, covering terminal energy consumption of 16 fossil fuels including raw coal, coke, crude oil, gasoline, kerosene, diesel, fuel oil, and natural gas. Using carbon emission factors from the IPCC Guidelines, industrial carbon emissions were calculated for each region. To ensure accuracy, the study focused on terminal energy consumption of fossil fuels, limiting the accounting scope to direct energy consumption in industrial production processes while excluding residential and agricultural sectors to effectively eliminate cross-sector emission source interference and reflect the carbon emission characteristics of industrial activities.

1.1.2 Land Use Data

Assessment of ecosystem carbon sink capacity relies on land use data. This study utilized the annual land cover dataset with 30m resolution released by Wuhan University, which provides nationwide distribution and area information for forests and grasslands, forming the basis for quantitative assessment of ecosystem carbon sinks. The study explicitly distinguished industrial land from other land use types. Industrial land primarily includes industrial parks, factory buildings, and storage facilities, which typically lack significant carbon sink functions due to intensive human activities and low vegetation coverage, and were therefore excluded from ecosystem carbon sink accounting. This distinction enables more accurate accounting of industrial impacts on ecosystem carbon sink resources.

1.1.3 Population Data

Population data were sourced from the *China Population and Employment Statistics Yearbook* (2000-2021). Regional permanent resident populations were used to calculate per capita industrial carbon emission ecological footprint, helping reveal horizontal equity in inter-regional environmental responsibility sharing.

1.1.4 Ecosystem Carbon Sequestration Capacity Data

Parameters for ecosystem carbon sequestration capacity were derived from existing research. Carbon sequestration capacities for forest and grassland were adopted from Xie Hongyu et al., taking values of 3.8096 $\mathrm{t \cdot hm^{-2}}$ and 0.9482 $\mathrm{t \cdot hm^{-2}}$, respectively. Considering China’ s vast territory and significant regional differences in land carbon sequestration capacity, this study applied ecological footprint equivalence factors calculated by Liu Moucheng et al. based on net primary productivity to equalize provincial land carbon sequestration capacities.

1.1.5 Data Processing and Quality Control

To ensure data accuracy and reliability, strict quality control and preprocessing were implemented: (1) Data cleaning to remove outliers and missing values, with reasonable interpolation for incomplete data. Due to data availability limitations, the study covers 30 provincial-level administrative regions, excluding Tibet, Hong Kong, Macau, and Taiwan. (2) Ecosystem parameter calibration based on authoritative research to ensure reflection of actual carbon sequestration capacity. (3) Spatial data processing using ArcGIS for land use data analysis to ensure spatial precision and representativeness in ecosystem carbon sink accounting. (4) Industrial land and ecosystem land differentiation by combining land use and industrial statistics to identify industrial land distribution and exclude it from ecosystem carbon sink accounting, thereby avoiding calculation errors due to industrial land complexity. This approach follows established research standards for land use type and ecosystem service function classification, ensuring accuracy in carbon sink accounting and model applicability in the industrial sector.

1.2 Model Framework 1.2.1 Three-Dimensional Carbon Footprint Model

The Three-Dimensional Carbon Footprint Model is a comprehensive analytical tool for assessing human impacts on ecosystem carbon cycles. By introducing “footprint size” and “footprint depth” dimensions, it fully characterizes industrial carbon emissions’ occupation of ecosystem carbon sink resources. In industrial contexts, regional industrial carbon emissions are absorbed and stored by the regional carbon sink system without discrimination. Carbon sink calculations are based on natural ecosystems (forests, grasslands) rather than industrial land itself, as industrial land lacks significant carbon sink functions due to intensive human activities and low vegetation coverage. Therefore, this study includes only forests and grasslands in ecosystem carbon sink accounting, which together account for approximately 90% of total carbon sink capacity.

The model components are calculated as follows:

1) **Industrial Carbon Emissions (ICE)**
Industrial carbon emissions are calculated using the IPCC method:

$$ICE = \sum (Q_{ei} \times S_{ei} \times D_{ei})$$

where ICE is total carbon emissions from industrial energy consumption (t), Qei is terminal consumption of energy type i (t), Sei is the standard coal conversion coefficient for energy type i ($\mathrm{kg} \cdot \mathrm{kg}^{-1}$), and Dei is the carbon emission coefficient ($\mathrm{t} \cdot \mathrm{t}^{-1}$). Standard coal conversion coefficients and carbon emission coefficients adopt IPCC values: raw coal (0.7143 $\mathrm{kg} \cdot \mathrm{kg}^{-1}$, 1.9003 $\mathrm{t} \cdot \mathrm{t}^{-1}$), coke (0.9714 $\mathrm{kg} \cdot \mathrm{kg}^{-1}$, 2.8604 $\mathrm{t} \cdot \mathrm{t}^{-1}$), crude oil (1.4286 $\mathrm{kg} \cdot \mathrm{kg}^{-1}$, 3.0202 $\mathrm{t} \cdot \mathrm{t}^{-1}$), gasoline (1.4714 $\mathrm{kg} \cdot \mathrm{kg}^{-1}$, 3.0426 $\mathrm{t} \cdot \mathrm{t}^{-1}$), kerosene (1.4714 $\mathrm{kg} \cdot \mathrm{kg}^{-1}$, 3.0179 $\mathrm{t} \cdot \mathrm{t}^{-1}$), diesel (1.4571 $\mathrm{kg} \cdot \mathrm{kg}^{-1}$, 3.0954 $\mathrm{t} \cdot \mathrm{t}^{-1}$), fuel oil (1.4286 $\mathrm{kg} \cdot \mathrm{kg}^{-1}$, 3.1705 $\mathrm{t} \cdot \mathrm{t}^{-1}$), and natural gas (1.3300 $\mathrm{kg} \cdot \mathrm{m}^{-3}$, 2.1655 $\mathrm{t} \cdot \mathrm{t}^{-1}$).

2) **Ecosystem Carbon Sink (CS)**
Ecosystem carbon sink refers to the amount of carbon absorbed and stored by ecosystems such as forests and grasslands per unit time:

$$CS = CS_f + CS_g = (NPP_f \times A_f \times E_f) + (NPP_g \times A_g \times E_g)$$

where CS is total carbon absorption by forest and grassland (t), CSf and CSg are carbon sinks of forest and grassland, Af and Ag are areas of forest and grassland (hm^2), NPPf and NPPg are carbon sequestration capacities of forest and grassland ($\mathrm{t} \cdot \mathrm{hm}^{-2}$), and Ef and Eg are equivalence factors for forest and grassland.

3) **Industrial Carbon Footprint (ICF) and Carbon Ecological Capacity (CEC)**

$$ICF = \frac{ICE}{NEP_f \times P_f + NEP_g \times P_g}$$

$$CEC = \frac{CS}{NEP_f \times P_f + NEP_g \times P_g}$$

where ICF is industrial carbon footprint (hm^2), CEC is carbon ecological capacity (hm^2), NEPf and NEPg are carbon sequestration capacities of forest and grassland ($\mathrm{t} \cdot \mathrm{hm}^{-2}$), Pf and Pg are carbon absorption proportions of forest and grassland, CS is regional carbon sink (t), and ICE is industrial carbon emissions (t).

4) **Industrial Carbon Deficit (ICD) and Surplus (ICS)**

$$ICD = ICF - CEC \quad (ICF > CEC)$$
$$ICS = CEC - ICF \quad (ICF < CEC)$$

where ICD is industrial carbon deficit (hm^2), ICS is industrial carbon surplus (hm^2), ICF is industrial carbon footprint (hm^2), and CEC is carbon ecological capacity (hm^2).

5) **Industrial Carbon Footprint Size (ICFsize) and Depth (ICFdepth)**

$$ICF_{size} = \min(ICF, CEC)$$
$$ICF_{depth} = 1 + \frac{ICF - CEC}{CEC}$$

where ICFsize is regional industrial carbon footprint size (hm^2), ICFdepth is regional industrial carbon footprint depth (dimensionless), ICF is industrial carbon footprint (hm^2), and CEC is carbon ecological capacity (hm^2). When ICF $\leq$ CEC, ICFdepth = 1, indicating that regional carbon sink flow resources can fully absorb annual industrial carbon emissions. When ICF $>$ CEC, ICFdepth $>$ 1, indicating that carbon sink flow resources are insufficient and carbon sink stock resources are being consumed.

1.2.2 Spatial Autocorrelation Analysis

Spatial autocorrelation analysis is a statistical method for evaluating geographic clustering characteristics and spatial dependence. It reveals distribution patterns and temporal evolution trends of variables in space. This study combines global spatial autocorrelation analysis (Global Moran' s I) and local spatial autocorrelation analysis (LISA clustering and transition) to analyze spatio-temporal dynamics of regional industrial carbon emissions. Global Moran' s I measures overall spatial clustering, ranging from -1 to 1, where positive values indicate spatial positive correlation (similar values cluster), negative values indicate spatial negative correlation (similar values disperse), and values near zero indicate random distribution. Temporal trends in Global Moran' s I are used to analyze spatio-temporal patterns and clustering trends of industrial carbon emissions. Local spatial autocorrelation identifies local clustering areas, including high-high, low-low, high-low, and low-high clustering types, revealing spatial heterogeneity and evolution patterns of regional carbon emissions.

1.2.3 Quadrant Clustering Analysis

Quadrant clustering analysis is a dual-indicator clustering method for identifying and classifying regional characteristic differences. This study employs quadrant clustering analysis combining industrial carbon footprint size and depth to classify regional industrial carbon emission characteristics. The study area is divided into four quadrants: Quadrant I (Core Mitigation Zone) with high size and depth requiring priority mitigation; Quadrant II (Critical Mitigation

Zone) with low size but high depth requiring focused mitigation; Quadrant III (Observation Zone) with low size and depth requiring continuous monitoring; Quadrant IV (Buffer Zone) with high size but low depth requiring buffered mitigation. This method provides scientific basis for differentiated mitigation strategies by visually demonstrating inter-regional differences.

2. Results

2.1 Dynamic Characteristics of Industrial Carbon Emissions 2.1.1 Temporal Trends

China' s industrial carbon footprint (ICF) exhibited a "rapid rise -temporary decline -high-level fluctuation" pattern from 2000 to 2021 [Figure 1: see original paper]. During the rapid ascent phase (2000–2011), accelerated industrialization and urbanization drove concentrated release of heavy chemical production capacity, with persistently high energy consumption leading to rigid growth in industrial carbon emissions. During this period, ecosystem carbon sink resources faced sharply increased demand from industrial activities, and ecosystem carbon sequestration capacity struggled to meet growing emission demands, gradually approaching saturation and creating substantial ecosystem pressure.

Entering the adjustment and fluctuation phase (2012–2021), emission reduction adjustments in high-energy-consuming industries slowed the growth rate of industrial carbon emissions, with carbon emission intensity decreasing in some sectors and ecosystem pressure partially alleviated. However, capacity expansion driven by economic recovery partially offset these reductions, maintaining industrial carbon emissions at high fluctuation levels. Additionally, carbon sink gains from projects such as returning farmland to forest and shelterbelt systems experienced lag effects, causing ecological restoration delays and failing to effectively curb the declining trend in ecosystem carbon sequestration capacity.

Overall, ICF grew at an average annual rate of 7.05% from 2000 to 2011, reaching 1.79 hm^2 per capita. After 2012, policy regulation and economic structural adjustment slowed ICF decline to 1.06% annually, dropping to 1.50 hm^2 per capita by 2021, though remaining at a high level. This trend indicates that occupation of ecosystem carbon sink flow resources by industrial carbon emissions expanded rapidly in the early stage, then moderated under policy guidance, but overall pressure remains substantial.

Meanwhile, industrial carbon footprint depth (ICFdepth) remained around 1, indicating that industrial carbon emissions roughly balanced with annual ecosystem net absorption, without large-scale consumption of carbon sink stock resources. However, as carbon ecological capacity (CEC) declined continuously at 0.43% annually, the ecosystem carbon sink threshold is projected to decrease to 8.60$×10^{8}$ t by 2030. If industrial carbon emissions maintain current levels, they may breach this threshold, causing ecosystem deficits. This suggests that although carbon sink stock resources have not yet been consumed on a large scale, future ecosystem risks are gradually accumulating.

2.1.2 Spatial Distribution Patterns

Using the natural breaks method, industrial carbon footprint size (ICFsize) and depth (ICFdepth) were classified into low, relatively low, medium, relatively high, and high value zones. Results show that China' s industrial carbon footprint size and depth exhibited significant regional disparities and phased characteristics from 2000 to 2021, reflecting dynamic relationships between regional industrial restructuring and ecosystem carrying capacity.

Industrial carbon footprint size demonstrated an "east-first-rise-then-fall, central-west-continuous-rise" gradient pattern [FIGURE:2, FIGURE:3]. In 2000, nationwide growth was common. Central and western regions such as Inner Mongolia and Shaanxi saw ICFsize rise to 2.15 hm^2 and 2.18 hm^2 per capita due to absorbing energy-intensive industries from the east, while Yunnan and Guizhou reached 2.26 hm^2 and 2.19 hm^2 per capita under the Western Development Policy. Fujian' s ICFsize increased to 2.26 hm^2 per capita due to receiving industrial transfer from the Yangtze River Delta. Although Ningxia remained in the low-value zone (0.83 hm^2 per capita), its average ICFsize reached 3.77 hm^2 per capita, reflecting the combined impact of resource-based economy and ecological vulnerability. By 2021, eastern regions showed overall decline, with Zhejiang and Fujian reducing to 0.73 hm^2 and 1.70 hm^2 per capita through eliminating backward production capacity. Central and western regions remained in medium-high value zones due to high coal consumption proportions. Eastern regions maintained low levels (0.76–1.92 hm^2 per capita) through industrial upgrading and policy regulation, while central and western regions reached 1.5 times eastern levels due to absorbing energy-intensive industries, reflecting regional differences in industrial layout and energy consumption patterns.

Industrial carbon footprint depth showed a bipolar pattern of local high-level rise and overall low-level maintenance [FIGURE:2, FIGURE:4]. During the study period, ICFdepth remained stable at 1 for most regions nationwide. However, core economic zones such as Shanghai (1.5), Jiangsu (1.5), and Tianjin (1.5) formed contiguous overload zones with spatial spreading trends. This primarily resulted from highly concentrated industrial carbon emissions and high emission intensity per unit land in Shanghai, lagging clean transformation in Jiangsu' s high-carbon industries, and carbon sink space compression due to construction land expansion in Tianjin. This pattern further highlights contradictions between unbalanced regional development and ecosystem carrying capacity, necessitating differentiated policy design, regional collaborative governance, and ecological restoration measures to optimize industrial carbon emission spatial layout and achieve dynamic balance between industrial development and ecological protection.

2.1.3 Spatio-temporal Migration Trends

China' s industrial carbon footprint size and depth exhibited "inland, clustered, and peripheral" migration trends from 2000 to 2021, revealing dynamic evolution of inter-regional industrial carbon emissions and their ecosystem impacts.

Global spatial autocorrelation analysis shows that the Global Moran’ s I for industrial carbon footprint size (ICFsize) increased from 0.204 to 0.455, indicating gradually strengthening spatial clustering . The Global Moran’ s I for industrial carbon footprint depth (ICFdepth) showed an “inverted U” pattern, rising from 0.313 to 0.463 and then falling back to 0.336, suggesting that spatial clustering of industrial carbon emissions evolved from initial random distribution to local agglomeration, though depth clustering weakened in later periods.

Local spatial autocorrelation analysis (LISA clustering and transition) further reveals spatio-temporal migration characteristics . Overall, industrial carbon emissions show inland, clustered, and peripheral migration trends. The Central Rise Belt (Hunan, Jiangxi, Anhui, Henan) formed high-value clusters while absorbing eastern energy-intensive industries, though size and depth transitions were not synchronized. The Southwest Resource Region (Guizhou, Yunnan) attracted high-load energy industries based on hydropower and mineral resources, shifting industrial carbon emissions from “point high values” to “clustered diffusion.” Developed regions (Guangdong, Beijing) reduced industrial carbon emissions through industrial upgrading and policy relocation, but transferred emission pressure to surrounding areas (Guangxi, Hebei) through industrial chain linkages. Peripheral areas (Hainan) formed isolated carbon emission hotspots, with geographical isolation limiting integration with regional industrial carbon networks.

2.2 Industrial Carbon Emission Reduction Potential Analysis

Using quadrant clustering analysis proposed by Chen Mingxing et al., standardized industrial carbon footprint size and depth indicators for 30 provinces were classified into four mitigation zones: Core Mitigation Zone (Quadrant I), Critical Mitigation Zone (Quadrant II), Observation Zone (Quadrant III), and Buffer Zone (Quadrant IV) .

The **Core Mitigation Zone** (Quadrant I) includes Guangdong and other regions with high industrial carbon emission intensity and carbon sink resource overload risks. Mitigation strategies should focus on carbon capture and storage technology and industrial zero-carbon technology applications while strictly controlling high-carbon industry expansion. For example, Guangdong has built carbon management infrastructure networks in the Daya Bay Petrochemical Zone and implemented hydrogen metallurgy technology integration in the Zhanjiang steel base, exploring systematic decarbonization pathways for high-carbon-intensity parks.

The **Critical Mitigation Zone** (Quadrant II) includes Tianjin, Jiangsu, Shandong, and Shanghai, characterized by high depth but relatively low size, indicating carbon sink stock resource depletion risks. Mitigation strategies should emphasize renewable energy substitution, circular economy promotion, and ecological compensation mechanisms. Shandong has optimized its energy structure through constructing wind-solar bases on saline-alkali tidal flats, combined with waste heat recovery and solid waste recycling systems in aluminum industrial parks, forming a closed-loop model for heavy industry green transformation.

The **Observation Zone** (Quadrant III) includes Beijing, Hebei, Jilin, Anhui, Henan, and other provinces that long-term depend on carbon sink flow resources to compensate for industrial carbon emissions, requiring prevention of long-term emission pressure. Strategies should focus on preventive monitoring and low-carbon guidance, with ecological restoration. Xinjiang, for instance, has promoted coupling technology applications between renewable energy (wind, solar) hydrogen production and coal chemical industry, constructing full-process carbon monitoring platforms covering key energy and chemical bases to accelerate clean energy substitution while ensuring energy supply security.

The **Buffer Zone** (Quadrant IV) includes Sichuan, Guizhou, Yunnan, Heilongjiang, Inner Mongolia, and other provinces where carbon sink resources can fully support industrial carbon emissions but require vigilance against potential load risks. Mitigation strategies should highlight ecological resource value transformation while emphasizing resource protection and sustainable utilization to avoid emission rebound. For example, Pu' er City in Yunnan has established dynamic balance mechanisms between industrial carbon emissions and ecological carbon sequestration through coordinated forestry carbon sink development and clean energy base operations, providing a sustainable development paradigm for carbon sink resource-abundant regions.

3. Discussion

This study calculates China' s industrial carbon footprint from 2000 to 2021 using the Three-Dimensional Ecological Footprint Model, revealing its spatio-temporal evolution characteristics and emission reduction potential. The spatio-temporal differences in China' s industrial carbon footprint (ICF) and carbon ecological capacity (CEC) reflect the dynamic game between economic growth and ecological protection. The "scissors difference" phenomenon between ICF and CEC during the study period reveals deep contradictions between industrial development and ecological protection, demonstrating the enormous pressure on ecosystems during economic growth model transformation. This change represents both a microcosm of industrialization and reflects the importance of policy regulation and technological innovation. Particularly for ecologically fragile arid and semi-arid regions with limited carbon sequestration capacity vulnerable to disturbance, the risk of stock depletion from industrial transfer is especially prominent, easily triggering chain reactions of ecosystem functional degradation. Therefore, central and western carbon sink stock consumption risks and eastern green technology spillover potential require focused attention.

Consistent with existing research [6,27-28], the spatio-temporal distribution of provincial industrial carbon footprint size and depth reveals gradient transfer characteristics of China' s industrial carbon emission pressure. Temporally, the trend shows a shift from eastern flow overload to inland stock depletion;

spatially, a three-tier pattern is gradually forming with eastern technological remediation, central pressure absorption, and western ecological barriers. The inland, clustered, and peripheral migration trends of provincial industrial carbon footprint size and depth are increasingly reaching ecologically fragile arid and semi-arid regions. This essentially represents spatial mapping of the game among regional development model choices, policy interventions, and resource endowment differences, requiring coordinated efforts in industrial layout, policy guidance, technological upgrading, and ecological protection to avoid negative effects such as economic growth dependence on high-carbon models and geographic pollution transfer through industrial relocation.

Furthermore, the designation of four mitigation zones reflects the complexity of spatial imbalance between industrial carbon emissions and carbon sink resources. Under the framework of emission reduction and carbon sink enhancement, different regional industrial carbon emission characteristics and resource endowments determine mitigation strategy differences. Therefore, promoting dynamic matching between industrial carbon emission spatial patterns and ecological carrying capacity constitutes an important pathway for achieving positive interaction between economic development and ecological protection [29]. Additionally, ecosystem carbon sinks are not necessarily better when larger; their development must match industrial emission reduction progress to avoid both premature peaking of carbon sink capacity leading to sudden later mitigation pressure and lagged carbon sink construction affecting overall carbon neutrality goals, consistent with findings by Piao Shilong et al. [30].

Despite revealing spatio-temporal evolution characteristics and mitigation potential of China’ s industrial carbon footprint, this study has limitations. First, at the model application level, data accuracy may be affected by climate change, land use conversion, and biases in ecosystem carbon sequestration capacity parameters. The model assumes relatively stable ecosystem carbon sink capacity without fully considering dynamic impacts of extreme weather events and urban land use changes. Second, at the spatial scale level, provincial administrative divisions may mask significant differences at finer scales; for instance, resource-based versus non-resource-based cities within the same province may have key spatial details weakened by provincial-scale processing, making it difficult to capture spatial heterogeneity from urban development model differences. Future research should improve data accuracy by combining remote sensing and field surveys to optimize ecosystem parameters for better simulation of carbon sink capacity changes, and conduct more detailed analyses at municipal or county scales.

4. Conclusions

Based on the Three-Dimensional Ecological Footprint Model, this study calculates the industrial carbon footprint of 30 Chinese provinces from 2000 to 2021, analyzing regional industrial carbon emission dynamic spatio-temporal evolution characteristics through footprint size and depth dimensions, and exploring mitigation potential across different regions. Main conclusions are:

1) China' s industrial carbon footprint (ICF) shows a "rapid rise -temporary decline -high-level fluctuation" nonlinear pattern. From 2000 to 2011, ICF grew at 7.05% annually, followed by an 8.87% decline in 2012, then maintained 1.94% average annual fluctuation. Meanwhile, carbon ecological capacity (CEC) declined continuously at 0.43% annually, reflecting systematic weakening of ecosystem carbon sequestration capacity.
2) Provincial industrial carbon footprint spatial distribution shows significant regional differences. Size (ICFsize) demonstrates an "east-first-rise-then-fall, central-west-continuous-rise"gradient pattern, while depth (ICFdepth) shows bipolar characteristics of local high-level rise and overall low-level maintenance. High-depth regions such as Shanghai, Jiangsu, and Tianjin form overload zones in core economic belts with spatial spreading trends.
3) Provincial industrial carbon footprint exhibits inland, clustered, and peripheral spatio-temporal migration trends, characterized by enhanced size clustering and local depth dispersion with multi-pole reconstruction. Central regions like Hunan, Jiangxi, Anhui, and Henan simultaneously increased in both size and depth when absorbing eastern industrial transfer. Western regions including Inner Mongolia, Shaanxi, Guizhou, and Yunnan formed contiguous high-value zones as industrial carbon emission clusters. Peripheral regions like Hainan formed isolated high-carbon pressure zones due to free trade port policies promoting petrochemical and aviation logistics expansion, though geographical isolation limited industrial carbon network connections with mainland provinces.
4) Significant differences in mitigation potential exist across regions, revealing the complexity of spatial imbalance between industrial carbon emission pressure and carbon sink resources. Regions with high size and depth have large mitigation potential and should adopt mandatory reduction measures; regions with low size and depth require preventive monitoring and ecological restoration. Quadrant clustering analysis clarifies mitigation strategy choices for each region, providing scientific basis for differentiated policy design.

5. Recommendations

To achieve coordinated progress in industrial low-carbon development and ecological protection, the following comprehensive measures are proposed based on regional characteristics:

1) **Differentiated Carbon Emission Standards**: Formulate region-specific carbon emission standards based on ecological carrying capacity and carbon footprint characteristics. Eastern regions should promote carbon capture and storage (CCS) and zero-carbon technologies to reduce carbon sink occupation, while central and western regions should advance

energy transformation and ecological restoration to optimize industrial structure.

2) **Cross-regional Ecological Compensation**: Establish cross-regional ecological compensation and carbon sink trading mechanisms, enabling eastern regions to purchase carbon sink quotas from central and western regions to achieve two-way capital and carbon sink flows and promote regional ecological balance.
3) **Eco-friendly Technology Innovation**: Promote ecological restoration and green electricity substitution technologies, pilot low-carbon technology upgrades in high-energy-consuming industries, and reduce industrial pressure on ecosystem carbon sinks.
4) **Dynamic Ecosystem Assessment**: Implement dynamic assessment and early warning for ecosystems, conduct continuous monitoring of carbon sink resources including forests, grasslands, and wetlands, establish degradation risk early warning mechanisms, and ensure stability of ecosystem service functions.
5) **Optimized Ecosystem Service Synergy**: Achieve synergistic enhancement between carbon sequestration and other ecological services such as biodiversity conservation and soil and water retention, improving overall regional ecosystem functions.
6) **Enhanced Ecological Education**: Strengthen ecological education and public participation, raise public awareness of ecological protection and low-carbon development, and promote green development concepts throughout society.

These measures provide scientific guidance for achieving coordinated progress in industrial low-carbon development and ecological protection.

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Note: Figure translations are in progress. See original paper for figures.