Journal of Cleaner Production 517 (2025) 145872

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

How does coupling coordination between industrial structure optimization and ecosystem services dynamically affect carbon emissions in the Yellow River Basin?

Ruixiang Xue [a], Runde Gu [b,*], Tzesan Ong [a,c]

[a] School of Business and Economics, Universiti Putra Malaysia, Seri Kembangan, 43300, Malaysia
[b] Institute of Geographical Sciences, Hebei Academy of Sciences (Hebei Engineering Research Center for Geographic Information Application), Shijiazhuang, 050011, China
[c] Department of Business Administration, Daffodil International University, Dhaka, 1207, Bangladesh

ARTICLE INFO

Keywords:
Industrial structural optimization
Ecosystem services
Carbon emissions
Yellow River Basin
Coupling coordination

ABSTRACT

In the Yellow River Basin (YRB), the dominance of coal mining and petrochemical industries, coupled with persistent ecosystem degradation, has contributed to increasing carbon emissions (CE). As industrial development has outpaced ecological restoration, aligning industrial structure optimization (ISO) with ecosystem services (ES) has become a strategic priority for emission control. This study examines the dynamic impact of ISO–ES coupling coordination on CE using panel data from 2011 to 2023. The coupling coordination degree model is employed to assess the ISO–ES interaction, while the dynamic spatial Durbin model captures temporal effects, spatial spillovers, and regional heterogeneity of ISO-ES coupling coordination on CE. The findings reveal notable progress in pollution control within the YRB, with steady improvements in ISO-ES coupling coordination; however, carbon emissions continue to grow, albeit slowly. Pronounced spatial spillover effects were also identified, such that ISO-ES coupling coordination impacts not only the YRB's carbon emissions but also those of adjacent regions. Dynamic analysis further found that while ISO-ES coupling coordination significantly reduces carbon emissions, its effect gradually weakens over time. In terms of heterogeneity, the negative impact of ISO-ES coupling coordination on carbon emissions appears to diminish from upstream to downstream regions, exhibiting a converging trend. This study provides empirical evidence to support the implementation of differentiated incentives, dynamic monitoring mechanisms, and the establishment of a regionally coordinated carbon trading system, thereby contributing to the advancement of national clean production transformation.

1. Introduction

In ecologically sensitive and industrially concentrated areas, managing carbon emissions (CE) has become a primary challenge for global sustainable development. China's Yellow River Basin (YRB) currently faces this issue directly. Accounting for 80 % of the nation's coal and oil output, the region also generates 25 % of the country's GDP (Xia et al., 2023). The persistent high CE levels stem from the energy-intensive industrial framework and substantial ecosystem damage (Feng et al., 2024). Although this industrial setup has driven regional economic growth, it has also imposed considerable environmental strain, causing land degradation, water contamination and public health concerns (Rong et al., 2023). Through the Outline for Ecological Protection and High-Quality Development of the YRB, the Chinese government has urged a coordinated shift in ecosystem management and industrial restructuring. This effort aims to manage CE while promoting cleaner production methods (Zhang et al., 2024). Within this policy framework, the interaction between industrial structure optimization (ISO) and ecosystem services (ES) plays a vital role in reducing CE.

ISO involves improving resource allocation and steering the economy toward industries with higher value, lower energy use and reduced emissions (Gong et al., 2023). Natural ecosystems offer ES such as climate regulation, water retention and biodiversity support (Li et al., 2024a). These services can increase carbon absorption, enhancing environmental systems' overall regulatory and supportive capacity (Chen et al., 2024). Previous research has typically examined the effects of ISO and ES on CE separately. However, studies focused on regions like the YRB and the Yangtze River Economic Belt suggest that shifting from

* Corresponding author.
E-mail addresses: gs65214@student.upm.edu.my (R. Xue), rundegu@stud.tjut.edu.cn (R. Gu), tzesan@upm.edu.my (T. Ong).

https://doi.org/10.1016/j.jclepro.2025.145872
Received 18 February 2025; Received in revised form 7 May 2025; Accepted 29 May 2025
Available online 31 May 2025

energy-intensive to higher value, lower energy industries increase energy efficiency and reduces CE at its origin (Wang and Li, 2024; Liu et al., 2021). Moreover, through carbon absorption, oxygen release and climate regulation, ES help mitigate CE (Qu et al., 2024; Zhao et al., 2020).

Yet, reliance on static methods such as ordinary least squares (OLS) or the spatial Durbin model (SDM), along with a single-variable focus, has limited understanding of the interactive effects between ISO and ES and their changing nature over time. ISO as well as ES show strong coupling rather than acting independently, as demonstrated by several scholars (Song et al., 2025; Pan et al., 2024). Changes in land use intensity driven by ISO influence ES functions, while ES also guide or limit the spatial distribution of industrial activities (Yuan et al., 2024). Research further points to spatial clustering effects in regional ISO and external influences exerted by ES (Li et al., 2025). These features suggest that coordinating ISO and ES development is a long-term, evolving process involving spatial diffusion (Sun et al., 2019; Wen et al., 2024). However, since ISO and ES belong to socioeconomic and ecological systems rooted in different disciplines, existing studies lack a comprehensive approach to integrating their combined effects on CE.

To fill this gap, this study uses panel data from the YRB covering 2011 to 2023 to explore the evolving effect of ISO-ES coupling coordination on CE. It addresses several key questions: Does the coordination between ISO and ES influence CE levels? Are there spatial spillover effects in adjacent regions? How does this influence change over time? Do these effects vary among upstream, midstream and downstream subbasins? To answer these, the study develops a framework combining the coupling coordination degree model (CCDM) and the dynamic spatial Durbin model (DSDM). CCDM measures the ISO-ES coupling coordination, while DSDM captures temporal changes, spatial spillovers and regional variations in CE effects. Fig. 1 presents the technical roadmap. The study therefore pursues three aims: (1) analyzing the spatiotemporal patterns of ISO-ES coupling coordination and CE; (2) evaluating the dynamic and spatial spillover impacts of ISO-ES coordination on CE; and (3) exploring regional differences across sub-basin zones.

This study makes several contributions. Firstly, it innovatively incorporates Industrial ISO and ES into a unified theoretical framework to systematically examine their impact on CE in the YRB. This provides a theoretical basis for low-carbon governance in regions characterized by both ecological fragility and industrial concentration. Secondly, by employing the DSDM, the study identifies the effects of ISO-ES coupling coordination on CE across short-term and long-term dimensions, as well as through direct and indirect channels. This offers practical insights for optimizing regional layouts and spatial-management strategies in high-emission industries such as energy, metallurgy and building materials. In addition, the study reveals the spatiotemporal evolution characteristics of key variables that can inform the evaluation and optimization of environmental governance policies. An example is the Outline for Ecological Protection and High-Quality Development of the YRB, particularly in promoting clean production and ecological protection. Finally, through heterogeneity analysis, the study provides empirical evidence to support the development of localized, region-specific CE control strategies.

The subsequent sections of this study are organized as follows: Section 2 reviews the theories and hypotheses. Section 3 describes the data and methodology. Section 4 reports the analysis results. Section 5 is the discussion. Section 6 presents the conclusions, implications, and some recommendations for future work.

2. Theoretical review and hypotheses

2.1. The effect of ISO-ES coupling coordination on CE

This study is grounded in general systems theory. According to this theory, complex systems are composed of multiple, interdependent subsystems (Laszlo, 2024). The overall performance of a system depends not only on the optimization of each subsystem but also on the coordination between them (Cabrera and Cabrera, 2023). ISO and ES represent the economic and ecological subsystems of a region, respectively (Ding and Eldridge, 2024). Their degree of coordination reflects the region's systemic integration and sustainability (Jing et al., 2024). This study introduces the concept of ISO-ES coupling coordination, which refers to the degree of alignment and synergy between industrial systems and ecosystem systems in terms of development levels and structural characteristics (Li et al., 2024b). A higher coupling coordination level indicates that the region achieves dynamic coordination by optimizing industrial layouts and enhancing ES functions simultaneously.

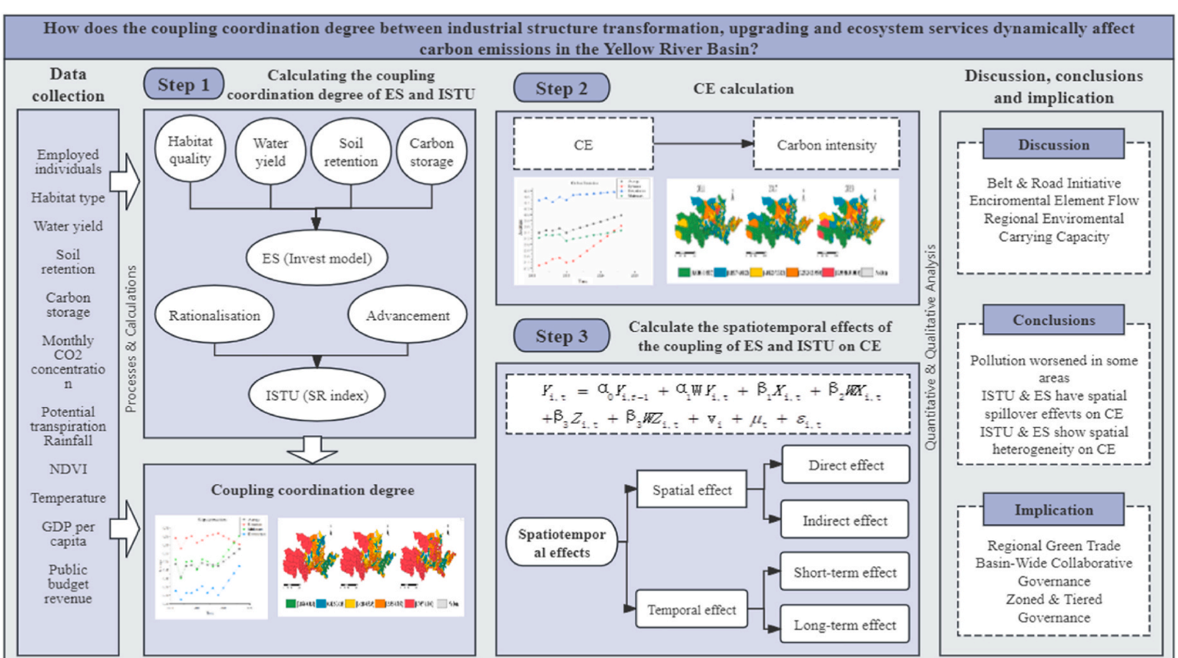

Fig. 1. Technical roadmap for evaluating the dynamic impact of ISO–ES coupling coordination on CE.

Prior studies in the literature have shown that promoting ISO in the YRB can reduce high-carbon industries and facilitate green substitution, thereby lowering CE intensity at the source (Cheng et al., 2025). Meanwhile, ES contributes to carbon absorption through carbon-sink regulation and environmental-buffering functions (Chen et al., 2024). Scholars have found that ISO and ES are not independent of each other but exhibit significant coupling relationships in areas such as land use, spatial patterns, and resource allocation (Pan et al., 2024; Song et al., 2025). Therefore, promoting the coupling coordination between ISO and ES helps to balance carbon source control and carbon sink enhancement, thereby improving overall emission reduction outcomes.

This study further examines how the coordination between ISO and ES affects CE. When the ISO-ES coupling coordination level is high, it suggests a synchronized advancement of industrial green transformation and ecosystem enhancement. In such cases, regions can control carbon source expansion through industrial optimization while strengthening carbon-sink capacity through ecological improvements, thereby improving overall CE management from both the source and the sink. Conversely, when ISO and ES are imbalanced and poorly matched, resource waste, environmental degradation, and CE rebounds are more likely to occur. Therefore, we propose that.

H1. ISO-ES coupling coordination has a significant negative impact on CE.

2.2. *The spatial spillover effect of ISO-ES coupling coordination on CE*

According to ecological modernization theory, economic development and ecological conservation can reciprocally support one another through industrial upgrading, technological innovation, and institutional restructuring (Abbass et al., 2025). This means that within an environmentally-friendly development framework, advancements in ES, technology, and industrial structure can positively impact environmental quality (Qu et al., 2024). This effect does not only take place locally but can also spill over to other areas through technology diffusion and resource distribution (Li et al., 2024a). The literature empirically demonstrates this mechanism. For example, Bai et al. (2023) showed that ISO and ES have significant spillover impacts on regional ecological protection and economic cooperation in China's Xin'an River Economic Belt. Tao et al. (2024) also proved that ISO alleviates CE not only locally but also in nearby areas by technology dissemination. Also, Liu et al. (2024a) found that improving ES in the management of water resource basins has a spatial spillover influence on CE.

In terms of the YRB region, coupling coordination between ISO and ES can generate low-carbon outcomes, which can flow to neighboring regions through market mechanisms, inter-regional collaboration, and environmental resource sharing. Given this potential spatial spillover effect, we hypothesize that.

H2. ISO-ES coupling coordination has a significant spatial spillover effect on CE.

2.3. *The dynamic effects of ISO-ES coupling coordination on CE*

The law of diminishing marginal returns states that the additional output from a factor decreases as investment continues, assuming other factors remain unchanged (Huerta de Soto, 2024). In ISO-ES coupling coordination, regions in early stages often face two main challenges: severely-damaged ES and highly uneven industrial structures. These factors together drive increased levels of CE (Wang and Li, 2024). Strong policy support during this period may create opportunities for improving the system. Moreover, the progress made by leading regions in improving ES and optimizing ISO is highly replicable (Li et al., 2024a). Their experience and advantages in resource allocation tend to spill over to neighboring areas, thereby promoting coordinated emission reductions (Cheng et al., 2025). As a result, reductions in CE typically accompany progress in coupling coordination.

When ISO and ES coupling coordination reaches a plateau, the scope for restoring ecological services tends to decline (Xia et al., 2023). Governance usually shifts its focus toward ecological margins or areas with weakened service functions. These changes raise management difficulties and cause diminishing marginal returns (Guo et al., 2024). ISO nears its capacity for further structural improvement, limiting the reduction of high-carbon industries and weakening the substitution effect of green industries (Wu et al., 2023). This structural change has weakened the advantages that leading regions had developed in ES and ISO practices, reducing their demonstrative and catalytic effects on surrounding areas and thereby diminishing the strength of spatial spillover effects (Wang et al., 2024; Meng et al., 2025). In this context, the marginal effect of ISO-ES coupling coordination on reducing CE gradually decreases. Also, growing pressures from economic expansion led some regions to return to high-carbon development paths (Bello-Pintado et al., 2023). This shift, driven by a preference for short-term economic benefits, tends to diminish the environmental gains achieved through improved ISO-ES coordination. Drawing on these insights, the following hypothesis is proposed.

H3. The negative impact of ISO-ES coupling coordination on CE gradually weakens over time.

3. Methodology

3.1. *Variable measurement*

3.1.1. *Independent variables*

(1) ISO

Researchers have used several indicators to measure ISO, such as regional GDP, the ratio of industry output and labor force distribution (Muhammad et al., 2022; Lin et al., 2023). These indicators, however, often fail to capture both the transformation and upgrading aspects of ISO completely. To address this limitation, we followed the method of Wang and Li (2024), combining the averages of industrial rationalization and advancement to create a broader ISO measure.

This study bases its industrial rationalization on the structural rationalization (SR) index developed by Gong et al. (2023). The SR index assesses how much labor input and output proportions vary across industries, indicating how efficiently resources are allocated within the industrial framework. Smaller differences suggest better resource allocation, reflecting a more rational structure. Larger differences imply significant resource misallocation. Equation (1) shows the formula for this calculation.

$$SR = \sum_{i=1}^{3} \left(Y_i \Big/ Y \right) |(Y_i/L_i)/(Y_i/L) - 1| \tag{1}$$

where Y represents the economic output of a region, L is the number of employed individuals, and i denotes industry type. As this indicator is inverse in nature, this study applied a reciprocal transformation.

To construct the index of industrial advancement, we referred to Hao et al. (2023) and measured it as the ratio of the value-added of the tertiary industry to that of the secondary industry.

(2) ES

Researchers commonly assess ES using two main methods. The first is the value equivalence method, which estimates ES value in monetary terms but overlooks spatial heterogeneity (Goulder and Kennedy, 2011; Costanza, 2020). The second method is artificial intelligence for ES (ARIES) model, which uses AI for region-specific assessments but faces regional constraints (Capriolo et al., 2020; Wang et al., 2022). As such, this study utilized the Integrated Valuation of ES and Tradeoffs (InVEST) model, which simulates ES changes under various land cover scenarios and provides spatial quantification without regional limitations.

It should be noted that the InVEST model has certain limitations in capturing the interactions among different ES, as it primarily focuses on spatial identification and quantitative analysis. However, since this study mainly examines the spatial spillover and dynamic effects, these limitations do not substantially affect the conclusions. Based on prior research (Ding and Eldridge, 2024; Liu et al., 2024b), we used InVEST to assess water yield, habitat quality, soil retention, and carbon storage.

Habitat quality was measured using threat sources, including cropland, built-up land, unused land, national highways, provincial highways, and railways. A threat factor table was constructed to assess habitat quality across the basin, represented by Equation (2).

$$Q_{xj} = H_j\left[1 - \frac{D_{xj}^2}{D_{xj}^2 + k^2}\right] \tag{2}$$

where j represents the habitat type; x is a grid cell; Q denotes habitat quality; H represents habitat suitability; D_{xj} indicates the threat level; and K is the half-saturation constant. The annual total water yield was estimated using climate, topography and land use data, as shown in Equation (3).

$$Y_{xj} = \left(1 - \frac{AET_{sj}}{P_x}\right) \times P_x \tag{3}$$

where Y represents the total annual water yield depth, AET is actual evapotranspiration, and P represents precipitation. The evapotranspiration coefficient and root depth were determined based on the literature and model manuals. Potential evapotranspiration was calculated with the Hargreaves-Samani method. To estimate soil retention, this study employed the difference between potential and actual soil erosion values, using Equations (4)–(6).

$$RKLS_X = R \times K \times LS_X \tag{4}$$

$$USLE_X = R \times K \times LS_X \times C_X \times P_X \tag{5}$$

$$SD_X = RKLS_X - USLE_X \tag{6}$$

where SD_x represents soil retention, LS_x is potential soil erosion, and $USLE_x$ refers to actual soil erosion. R_x (rainfall erosivity) was calculated using Wischmeier's formula. K_x (soil erodibility) was computed with the EPIC model. LS_x is the slope length factor, P_x is the soil conservation practice factor, and Cx is the vegetation cover management, as shown by Kpienbaareh et al. (2024). To measure carbon storage, this study adopted the calculation proposed by Ding and Eldridge (2024), as shown in Equation (7).

$$C = C_{above} + C_{below} + C_{soil} + C_{dead} \tag{7}$$

where C represents total carbon storage, including above-ground (C_{above}), below-ground (C_{below}), soil (C_{soil}), and dead organic (C_{dead}) carbon storage.

3.1.2. Dependent variable

Due to the severe lack of county-level CE data, this study estimates CE using nighttime light intensity as a proxy for regional economic activity. Following the methods and datasets of Chen et al. (2020), Liu and Zhu (2022), and Ma and Zhang (2025), a neural network model is used to fit the relationship between nighttime light data and provincial-level CE. Subsequently, the weights are determined through a back-propagation neural network. Based on the total nighttime light intensity at the county level, CE for each county is then estimated. Missing values are supplemented using linear interpolation. Previous studies have demonstrated that this nighttime light-based estimation strategy offers significant advantages in terms of accuracy and applicability, particularly when compared with traditional estimation methods based on fossil fuel consumption data (Huo et al., 2022).

3.1.3. Control variables

To minimize interference from other factors and enhance the accuracy of the study's conclusions, we referred to Li et al. (2024b) and Xue et al. (2024) to select six control variables from both geographic and socioeconomic dimensions: vegetation cover (NDVI), potential transpiration, rainfall, temperature, GDP per capita, and general public budget revenue. NDVI was calculated using the percentage of vegetation cover; potential transpiration and rainfall were determined using their annual cumulative values; temperature was based on the annual average; GDP per capita was computed using county-level GDP; and general public budget revenue was measured based on the total annual public budget revenue of the county.

3.2. Sample and data sources

The study sample comprised annual county-level data from the YRB between 2011 and 2023. After data cleaning and estimation, a total of 6500 observations were obtained. The data sources were as follows: CE, temperature, precipitation, and potential evapotranspiration data were acquired from the China Emission Accounts and Datasets, Meteorological Data Center; ES and NDVI data were derived from the Chinese Academy of Sciences; and ISO, GDP per capita, and public budget revenue data were obtained from county-level statistical yearbooks and statistical communiqués on national economic and social development (Table 1).

The study area encompassed 56 cities across nine provinces in the YRB, covering approximately 795,000 square kilometers and extending across eastern, central, and western China (Fig. 2). The YRB is a crucial ecological region, characterized by cropland, woodland, and grassland. However, due to the widespread distribution of loess and alluvial deposits, the region's ecosystem is fragile (Fig. 3). Its industrial structure is dominated by high-pollution industries, which rely on outdated technologies and operate inefficiently, resulting in the YRB accounting for more than 30 % of CE in the nation.

3.3. Model construction

3.3.1. CCDM

The CCDM is defined as a quantitative method for measuring the coordination level between two heterogeneous systems during their interaction process. This makes it suitable for analyzing the co-evolutionary relationship between ISO and ES. Based on the work by Ariken et al. (2021), a CCDM was constructed to calculate ISO-ES coupling coordination in the YRB. The min-max method was used to normalize S (ISO) and E (ES) within [0.01, 0.99] for further analysis.

Table 1
Variables name, units, and sources.

Type	Name	Unit	Source
Dependent Variable	CE	million tons	https://www.ceads.net/
Independent Variable	CCDISO-ES	unitless	http://www.stats.gov.cn/ http://www.nesdc.org.cn/
Control Variable	NDVI	%	https://search.earthdata.nasa.gov/search
	Potential transpiration	m	http://data.tpdc.ac.cn
	Rainfall	m	http://data.tpdc.ac.cn
	Temperature	°C	http://data.tpdc.ac.cn
	GDP per capita	RMB/person	http://www.stats.gov.cn/
	General public budget revenue	Million RMB/year	http://www.stats.gov.cn/

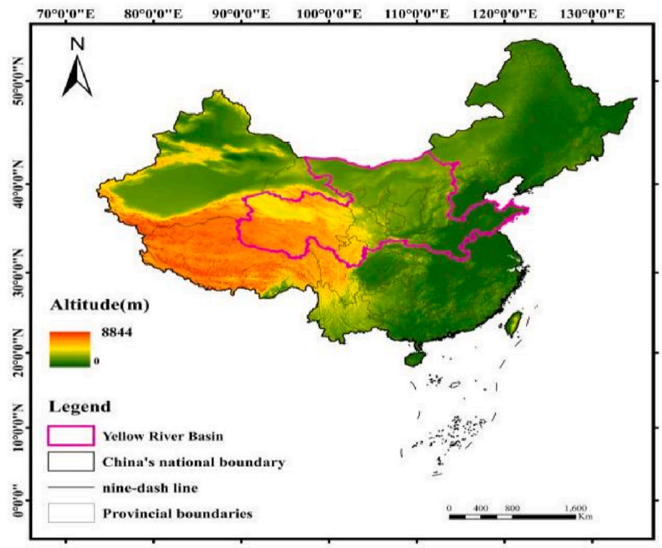

Fig. 2. Geographical location of the YRB in China.

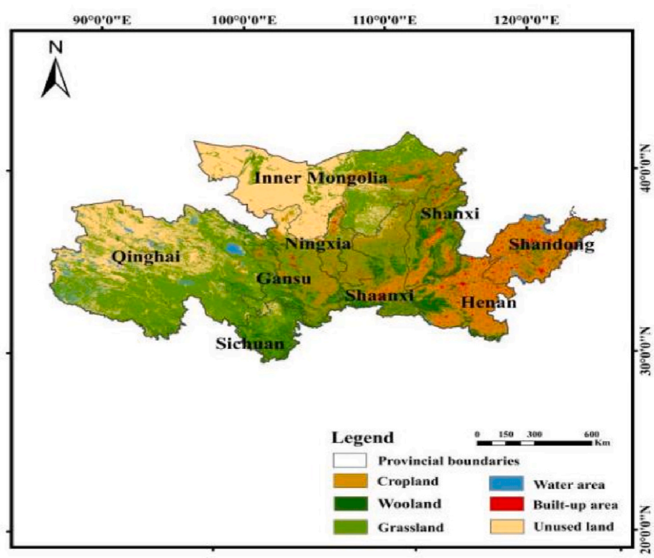

Fig. 3. Provincial divisions within the YRB.

Drawing on the physics concept of capacity coupling, the coupling function between ISO and ES in the YRB, as shown in Equation (8).

$$C = \sqrt[m]{\frac{S_C \times E_C}{(S+E)^2}} \tag{8}$$

where C represents the coupling degree of ISO and ES. As m represents the number of sub-systems, its value was set to 2 based on the two sub-systems (namely, socio-economic and ecological) in the study's framework. The ISO-ES coupling coordination level was then calculated using Equations (9) and (10) to objectively assess the coordinated development between ISO and ES in the YRB.

$$D = \sqrt{C \times T} \tag{9}$$

$$T = a \times S_C + \beta \times E_C \tag{10}$$

where D represents the degree of ISO-ES coupling coordination ($CCD_{ISO\text{-}ES}$) and T is the comprehensive index reflecting their coordination and benefits. This study adopts the equal weighting method. It assigns both α and β a value of 0.5 to reflect the equal importance of ISO and ES in promoting regional low-carbon development. This method has been heavily used in relevant studies (e.g., Shi et al., 2022; Zhang et al., 2024). It is suitable when subsystems contribute comparably to the overall system without a clear prioritization.

3.3.2. DSDM

Compared to the traditional SDM, the DSDM incorporates a lagged dependent variable, enabling a more comprehensive identification of the dynamic temporal and spatial effects of ISO-ES coupling coordination on CE (Gong et al., 2023). This approach overcomes the limitations of static models in capturing the dynamic impacts of such relationships (Li et al., 2024b). However, this approach also has certain limitations, such as increased model complexity and longer computation times, especially with large datasets or high-dimensional spatial structures. To address these issues, we used MATLAB with spatial econometric modules optimized for computational efficiency.

As mentioned earlier in this paper, robust ISO and ES in a region can decrease its pollution levels and subsequently spread its environmental gains to surrounding regions; this mechanism demonstrates the importance of spatial spillover. Additionally, due to older policies, ISO and ES often affect CE after a lagged period, which requires the consideration of temporal and spatial lag effects. Moreover, it is incorrect to assess the impact of ISO-ES coupling coordination on CE from a single perspective; its direct/indirect and short/long-term pathways necessitate a multi-faceted approach. We referred to the work of Alharbey and Ben-Salha (2024) and adopted the DSDM to fully capture this complex relationship. The model is specified in Equation (11).

$$Y_{i,t} = \alpha_0 Y_{i,t-1} + \alpha_1 WY_{i,t} + \beta_1 X_{i,t} + \beta_2 WX_{i,t} + \beta_3 Z_{i,t} + \beta_3 WZ_{i,t} + \nu_i + \mu_t + \varepsilon_{i,t} \tag{11}$$

Where Y represents CE, X refers to $CCD_{ISO\text{-}ES}$; Z denotes the control variable; v represents regional effects; and μ indicates temporal effects.

4. Empirical results

4.1. Analysis of temporal evolution trends

This study initially assessed temporal CE trends in the YRB and its sub-regions (i.e., upstream, midstream, downstream) between 2011 and 2023 (see Fig. 4). CE has shown a stable and gradual upward trend, indicating significantly worsening pollution. This trend became more pronounced after 2015, implying mounting pressure to mitigate CE in the YRB. Notably, we observed regional disparities in CE levels over

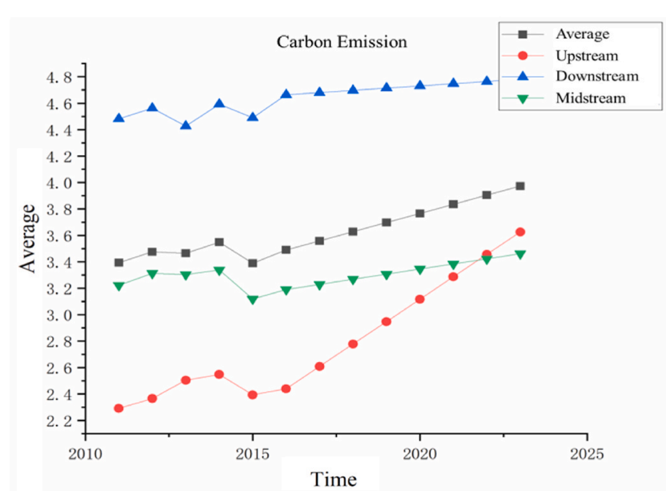

Fig. 4. Temporal evolution of CE in the YRB from 2011 to 2023.

time. Upstream sub-basins demonstrated the lowest CE, while midstream sub-basins showed average CE, and downstream sub-basins produced the highest CE. Nonetheless, emission levels in all three subregions converged monotonically in an upward growth trend. Specifically, CE in upstream regions increased from 2.2 in 2011 to 3.2 in 2023, with a substantial acceleration post-2015 that surpassed the midstream region. This spike can be attributed to upstream areas' fast-tracked economic development and industrialization, which calls for stronger emission-control efforts. On the other hand, CE in the midstream region generally oscillated around the 3.2 level over the study period. Its relative stability indicates some success in environmental protection and emission control. Finally, in the downstream region, CE grew from 4.4 in 2011 to 4.6 in 2023, potentially due to extensive industrial activities and denser populations. As such, more robust emission-control initiatives are required here.

Fig. 5 illustrates the temporal evolution of ISO-ES coupling coordination in the YRB from 2011 to 2023. The time-trend results show that since 2018, ISO-ES coupling coordination significantly increased across the YRB, suggesting notable progress in joint economic development and ecosystem improvements. Nevertheless, regional differences are apparent, with diverging growth rates and stepwise declines observed from upstream to downstream. Specifically, this study finds that the upstream regions had the best coupling coordination conditions, fluctuating around 0.6. The midstream region demonstrated moderate coupling coordination conditions with a rising trend that surpassed the upstream area starting in 2022. The downstream region exhibited the lowest coupling coordination conditions; however, since 2019, the coupling coordination has improved from 0.3 to 0.45 after targeted governance efforts.

This disparity can be attributed to differing regional development objectives. Upstream areas prioritize ecological conservation, as they have abundant natural resources and a relatively solid ecological foundation. They also actively promote the tertiary industry while limiting the environmental impacts of their primary and secondary industries. In contrast, midstream and downstream areas are more focused on economic development; even so, they have gradually recognized the importance of balanced development in recent years and, accordingly, have initiated industrial restructuring efforts.

4.2. Analysis of spatial evolution trends

Examining the spatiotemporal progression of ISO-ES coupling coordination alongside CE within the YRB, this study directly investigates whether their distribution shows spatial imbalances. The years 2011, 2017, and 2023 were chosen as key points for analysis. To illustrate the spatial changes over time, ArcGIS was employed to reveal the evolving patterns of distribution and regional coordination. The results are presented in Figs. 6 and 7. Fig. 6 illustrates the spatial changes of CE across the YRB from 2011 to 2023. CE followed a shifting pattern, rising from low to high emissions while moving from dispersed local spots towards more clustered regional groupings. Spatial imbalance became evident. Most regions, especially in 2011, displayed relatively low CE levels, mainly falling within the green (0.0080–1.8527) and blue (1.8527–4.0122) ranges. These values likely reflect the basin's early stages of industrial and urban development. By 2017, some areas experienced increased CE levels. Midstream and upstream cities, such as Lanzhou and Yinchuan, reached the orange range (7.2323–12.9598). The emergence of high-emission clusters suggests that policy-driven economic expansion and industrial growth have increased regional energy consumption and CE. In 2023, the spread of high-emission zones (red zone, 12.9598–39.0000) became more noticeable. Some cities, including Xining in Qinghai, Lanzhou in Gansu, and several in Inner Mongolia and Ningxia, stood out significantly. This trend aligns with the Belt and Road Initiative and policies encouraging regional industrial relocation. Upstream cities, through establishing manufacturing and infrastructure projects, experienced rapid economic growth, accompanied by a substantial rise in CE.

Fig. 7 illustrates the spatial evolution of the ISO-ES coupling coordination levels in the YRB for the years 2011, 2017, and 2023. Overall, the basin exhibited a relatively high level of coupling coordination, but regional disparities remained substantial. In 2011, the upstream areas had already achieved a high level of coupling coordination (red zone, 0.7057–1.0000), whereas the midstream and downstream regions contained extensive low coupling coordination areas (green, 0.1896–0.3132; blue, 0.3132–0.4218), indicating a weak foundation for the coupling between ISO and ES. By 2017, low-coordination areas in the midstream and downstream regions had significantly decreased, while orange (0.5335–0.7057) and red areas expanded, reflecting the positive effects of industrial upgrading and ecological protection policies on improving ISO-ES coupling coordination. In 2023, high coupling coordination zones further expanded, particularly around midstream urban clusters such as Zhengzhou and Jinan, demonstrating a continued enhancement of regional coupling coordination capabilities.

4.3. DSDM analysis

Table 2 results show that the Moran's I values range between 0.12 and 0.23 across the years, all being positive. This indicates a significant spatial clustering effect in CE, meaning that regions with higher or lower CE levels tend to be geographically adjacent. In contrast, a negative Moran's I would suggest spatial dispersion. Moreover, the Moran's I values are all significant, further confirming the presence of statistically significant positive spatial autocorrelation in CE. This suggests that CE does not occur in isolation but is significantly influenced by neighboring areas, exhibiting a typical spatial dependency. Therefore, this study employs spatial econometric models for further analysis.

A series of tests were conducted to accurately determine the suitable spatial model for this study (see Table 3 for results). First, the Hausman test results indicated that both temporal ($t = 290.42$, $p = 0$) and spatial ($t = 370.24$, $p = 0$) fixed effects were significant, necessitating the consideration of both factors in the analysis. Additionally, the Durbin-Watson (DW) test value was 0.2, which deviates significantly from 2, indicating the presence of first-order autocorrelation. Therefore, we introduced the lagged variable Y_{t-1} to address autocorrelation and reduce its negative effect on the model. Furthermore, the LM test results show that the statistics for LM-error (5349.8), LM-lag (3321.8), LM-robust_error (2036.47), and LM-robust_lag (8.47) are all significant, indicating the simultaneous presence of spatial lag and spatial error dependence. Therefore, the SDM was selected. Moreover, considering the strong autocorrelation revealed by the DW test, the model is further

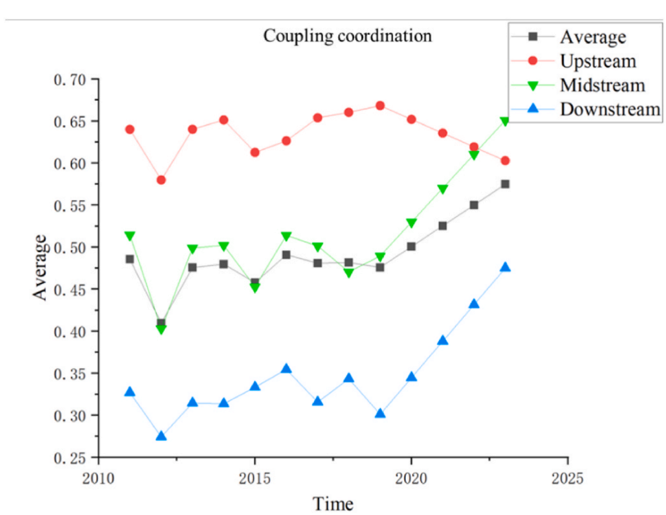

Fig. 5. Temporal evolution of ISO-ES coupling coordination in the YRB from 2011 to 2023.

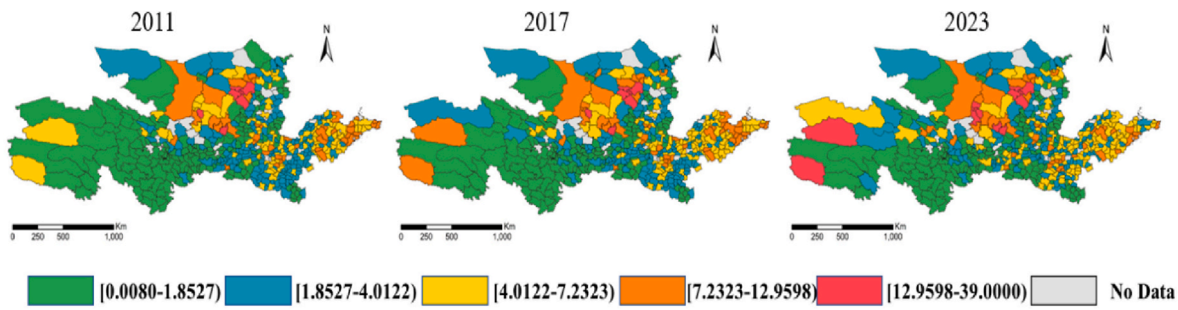

Fig. 6. Spatial evolution of CE in the YRB from 2011 to 2023.

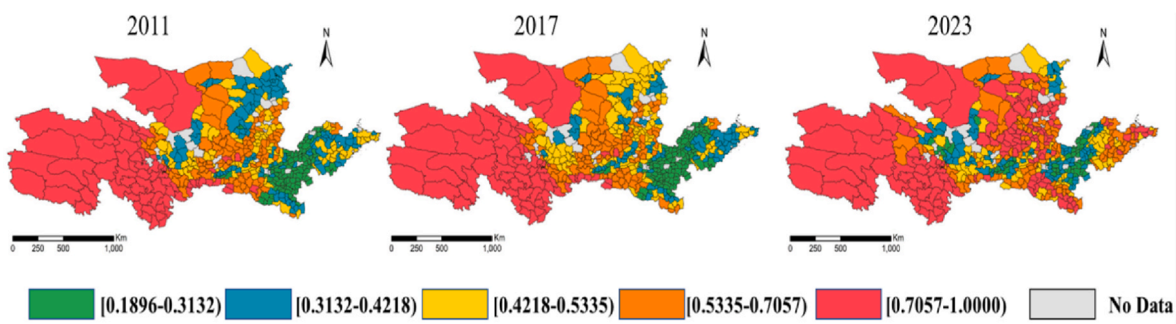

Fig. 7. Spatial evolution of ISO-ES coupling coordination in the YRB from 2011 to 2023.

Table 2
Spatial autocorrelation test (Moran I) of CE in the YRB.

Year	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
MoranI	0.14	0.12	0.14	0.17	0.15	0.16	0.16	0.19	0.22	0.22	0.22	0.23	0.23
t	9.35	8.16	9.20	11.07	9.84	10.72	10.82	12.33	14.26	14.64	14.75	14.91	15.31
p	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table 3
Diagnostic tests for selecting spatial econometric model specification.

	Time fixed effects	Spatial fixed effects	DW test	LM-error	LM-lag	LM-robust_error	LM-robust_lag
t value	290.42	370.24	0.2	5349.8	3321.8	2036.47	8.47
p value	0.00	0.00		0.00	0.00	0.00	0.00

extended to a DSDM by incorporating the lagged dependent variable to capture the temporal dynamic effects of ISO-ES coupling coordination on CE.

The Variance Inflation Factor (VIF) was used to test for multicollinearity. As shown in Table 4, no multicollinearity existed among the variables, as the mean VIF value of 1.4559 was well below the threshold of 10.

According to the regression results in Table 5, the ISO-ES coupling coordination index (CCDISO-ES) exerts a significant negative effect on CE across all three models. The coefficients are −4.20, −4.50, and −4.57, with a slight increase in magnitude. This can be attributed to the DSDM's incorporation of spatial lag variables and the lagged dependent variable, which distinguishes the coupling-coordination effects of local and neighboring regions, allowing for a more accurate identification of the local ISO-ES impact on CE. Furthermore, the DSDM results indicate that a 1 % increase in the coupling-coordination level leads to an average reduction of 0.0457 mt in CE, demonstrating the emission-reduction effect of ISO-ES coupling coordination. This suggests that the YRB can curb CE at the source by optimizing its ISO, while strengthening the carbon absorption capacity of ES at the terminal stage, ultimately contributing to environmental improvement. These findings support H1.

Table 4
VIF statistics of ISO–ES coupling coordination and control variables.

Variable	VIF
CCDISO-ES	1.2620
NDVI	1.8106
Potential transpiration	1.0101
Rainfall	1.6731
Temperature	1.0363
GDP per capita	1.6604
Public budget revenue	1.7385
Mean	1.4559

Meanwhile, the coefficient of W*CCDISO-ES is 4.30, indicating that a 1 % increase in the ISO-ES coupling-coordination level of neighboring regions leads to an average increase of 0.0430 mt in local CE. This suggests that improvements in neighboring regions' ISO-ES coupling coordination exert a positive spillover effect on local CE. Therefore, it is necessary to be cautious of potential issues such as industrial relocation and resource externalities when promoting ISO-ES coupling

Table 5
Regression results of OLS, SDM, and DSDM models on ISO–ES coupling coordination and CE.

	OLS	SDM	DSDM
CCDISO-ES	−4.20***	−4.50***	−4.57***
	(-26.79)	(-19.58)	(-20.25)
W*CCDISO-ES		3.93***	4.30***
		(9.49)	(13.44)
Y t-1			0.03***
			(2.96)
W*Y t-1			−0.07
			(-0.08)
NDVI	−2.99***	−1.29***	−1.50***
	(-15.30)	(-5.98)	(-6.92)
Potential transpiration	−0.21**	−0.21***	−0.24***
	(-2.51)	(-2.73)	(-3.05)
Rainfall	−0.11	0.21*	0.16*
	(-1.01)	(1.81)	(1.72)
Temperature	0.02***	0.02*	0.01
	(2.78)	(1.73)	(0.60)
GDP per capita	0.01***	0.01***	0.01***
	(25.55)	(20.93)	(21.95)
Public budget revenue	0.01***	0.01***	0.01***
	(41.95)	(36.89)	(37.14)
W*NDVI		0.34	1.17***
		(0.75)	(2.96)
W* Potential transpiration		0.47**	0.39**
		(2.38)	(1.97)
W* Rainfall		−0.30	−0.27
		(-1.09)	(-1.39)
W* Temperature		−0.02	−0.01
		(-1.36)	(-0.46)
W* GDP per capita		−0.01***	−0.01***
		(-9.21)	(-10.96)
W* Public budget revenue		−0.01***	−0.01***
		(-10.27)	(-13.48)
Con	5.74***		
	(30.32)		
ρ		0.96***	0.95***
		(153.91)	(67.42)
R^2	0.56	0.76	0.76
Nob	6500	6500	6000

coordination. This positive spillover effect may stem from spatial substitution of pollution, highlighting the importance of advancing cross-regional collaborative governance.

Regarding the control variables, the coefficient of NDVI is −1.50, indicating that a 1 % increase in regional vegetation coverage leads to a reduction of 0.015 mt in CE intensity. This suggests that improvements in vegetation coverage and enhanced water cycles contribute to carbon absorption and emission reduction. Conversely, precipitation (0.16) and temperature (0.01) show positive relationships with CE, implying that extreme climate conditions may indirectly increase infrastructure-repair demands and energy consumption, thereby raising CE. Moreover, both per capita GDP (0.01) and public fiscal revenue (0.01) have significant positive effects on CE, indicating that as economic activity expands, industrial output and energy demand increase, which in turn drives up CE.

In addition, the ρ for CE in the SDM and DSDM models was significant, with coefficients of 0.96 and 0.95, respectively, showing significant spatial spillover effects. A reduction of one unit in local CE results in a corresponding change of 0.96 or 0.95 in neighboring areas. The R^2 values of 0.76 for the SDM and DSM models furthermore surpassed that of the OLS model ($R^2 = 0.56$), validating that the inclusion of spatial effects enhances the model's explanatory power.

To further explore the dynamic impact of ISO-ES coupling coordination on CE, this study decomposes the regression results from the DSDM model into temporal and spatial effects. It separately estimates the short-term and long-term direct, indirect, and total effects. Additionally, considering the significant geographical differences within the YRB, the region is categorized into upstream, midstream, and downstream areas. A heterogeneity analysis is then conducted; the results are presented in Table 6. As shown in Table 6, ISO-ES coupling coordination significantly suppresses CE in both the short and long term across the YRB. The short-term total effect is −98.27, and the long-term total effect is −51.55. These results further support H1, which states that ISO-ES coupling coordination helps reduce CE.

Further decomposition shows that in the short term, the indirect effect (−92.89) is much larger than the direct effect (−5.38). Similarly, in the long term, the indirect effect (−46.26) remains greater than the direct effect (−5.29). This shows that improvements in local ISO-ES coupling coordination not only directly reduce local CE but also significantly promote emission reductions in neighboring areas through spatial spillover effects. This is because there are close ecological and economic linkages among regions within the YRB. Promoting improvements in ES, such as forest, grassland, and wetland restoration, can enhance regional climate conditions and air quality, thereby improving the capacity to mitigate carbon emissions in neighboring areas. Moreover, measures related to ISO are highly replicable and tend to diffuse across regions, enabling their carbon reduction effects to influence surrounding areas. The findings highlight strong externalities and regional linkages of ISO-ES coupling coordination, thereby supporting H2.

In addition, the absolute value of the short-term total effect (−98.27) is significantly larger than that of the long-term effect (−51.55). Furthermore, the short-term direct, indirect effect (−5.38, −92.89) is also notably greater than its long-term counterpart (−5.29, −46.26). These indicate that the inhibitory effect of ISO-ES coupling coordination on CE exhibits a marginal diminishing trend over time. Although the effect gradually weakens, it remains negative, thus supporting H3. This may be attributed to the diminishing marginal effects of ISO-ES coupling coordination measures. In the early stages of regional governance, efforts are typically focused on areas that are easiest to improve and offer the highest efficiency gains, resulting in significant emission reductions. However, as governance deepens, the remaining scope for improvement narrows, while the associated costs and implementation difficulties increase, leading to a gradual decline in marginal effectiveness. Such diminishing returns can extend to surrounding regions, thereby weakening the spatial spillover effect. This pattern is consistent with the environmental Kuznets Curve, which suggests that environmental improvements are most pronounced in the initial stages and tend to weaken over time.

The heterogeneity analysis further reveals differences in effect strength across regions. The results show that the negative impact of ISO-ES coupling coordination on CE gradually weakens from upstream to downstream areas, indicating a convergence trend. For example, in the short term, the direct, indirect, and total effects in the upstream region are −8.98, −49.38, and −58.35, respectively, which are notably stronger than those in the midstream (−4.14, −21.47, and −25.61) and downstream regions (−1.40, −5.13, and −6.53). A similar trend is observed in the long-term effects. These findings show that the governance effect of ISO-ES coupling coordination is strongest in the upstream areas, followed by the midstream, and weakest in the downstream regions. This pattern may be related to differences in regional environmental conditions and industrial structures. The upstream region is dominated by industries such as animal husbandry and crop farming, which align with local natural resource endowments and cause relatively low ecological disturbance. In promoting ISO-ES coupling coordination, it is easier to achieve the dual objectives of controlling carbon sources and enhancing carbon sinks, thereby leading to a more efficient carbon reduction response. In the midstream region, the level of economic development is moderate, and industrial restructuring is at a critical stage. Improvements in coupling coordination can thus promote industrial upgrading and ecological synergy, resulting in a notable reduction in CE. In contrast, although downstream regions serve as economic centers, they are subject to significant ecological pressure, and the response of ecosystem restoration tends to be relatively delayed.

Table 6
Heterogeneity analysis: results of spatiotemporal effect decomposition on ISO–ES coupling coordination and CE.

Variable	Period	Impact	DSDM	DSDMup	DSDMmid	DSDMdow
CCDISO-ES	Short-term	Direct	−5.38***	−8.98***	−4.14***	−1.40***
			(-17.18)	(-14.37)	(-9.18)	(-3.34)
		Indirect	−92.89**	−49.38***	−21.47***	−5.13***
			(-2.41)	(-4.21)	(-4.02)	(-3.38)
		Total	−98.27**	−58.35***	−25.61***	−6.53***
			(-2.54)	(-4.83)	(-4.57)	(-3.45)
	Long term	Direct	−5.29***	−8.79***	−4.03***	−1.40***
			(-18.11)	(-13.61)	(-9.07)	(-3.32)
		Indirect	−46.26**	−48.44***	−20.11***	−4.61***
			(-2.81)	(-3.16)	(-3.31)	(-3.03)
		Total	−51.55***	−57.23***	−24.15***	−6.01***
			(3.11)	(-3.65)	(-3.82)	(-3.26)
Control			Yes	Yes	Yes	Yes
R^2			0.76	0.79	0.80	0.71
p			0.95***	0.87***	0.84***	0.76***
			(67.42)	(35.60)	(33.93)	(26.11)

Meanwhile, the industrial structure is highly complex, with strong systemic inertia, leading to higher marginal costs for green transformation. These factors jointly constrain the effective realization of the ISO-ES coupling coordination's mitigation potential.

5. Discussion

This study analyzes the spatiotemporal evolution of ISO-ES coupling coordination and CE in the YRB. The results show that although regional CE control and ISO-ES coupling coordination have improved, the overall pressure for reduction remains high. This finding is consistent with Wei et al. (2024) and Huang et al. (2025), who argue that the growth rate of CE has slowed but has not yet reached an inflection point. Further analysis reveals that CE are increasing in the upstream areas, especially in Xining (Qinghai Province) and Lanzhou (Gansu Province). This trend is also supported by previous studies (Du et al., 2025; Zhong et al., 2025), highlighting that cities along the Belt and Road Initiative have encountered increasing environmental pressure due to urbanization, population mobility, and rising energy and transport demand. Moreover, policy documents such as the Guiding Opinions on Promoting the Formation of a New Pattern of Western Development in the New Era have proposed the development of key industries, including transportation and manufacturing, in western China (Yan et al., 2024). Although these initiatives aim to promote ecological protection in the long run, they are expected to cause short-term increases in CE.

In addition, this study demonstrates that the level of ISO-ES coupling coordination has a significant negative effect on CE. This result not only extends the findings of Qu et al. (2024), which focused on the inhibitory effect of individual variables such as ES on CE, but also deepens the discussion on the CE-macroeconomy relationship as explored by Assounga et al. (2025). Unlike most existing studies that concentrate on the impact of a single system on CE (Cheng et al., 2025), this study shifts the analytical perspective to the coupling coordination between ISO and ES, emphasizing their interaction as systems in regulating CE. This perspective is highly consistent with the core concepts of General Systems Theory, which highlight interaction and coordination between systems. From a quantitative perspective, the results show that a 1 % increase in ISO-ES coupling coordination can reduce approximately 0.0457 mt of CE. Although this reduction accounts for a relatively small share of the total CE in the YRB, it is of considerable significance at the local level. For high-emission countries, this amount offsets a substantial portion of their annual CE growth. Therefore, enhancing ISO-ES coupling coordination remains of great practical and policy significance in the ongoing process of carbon governance.

This study also finds that improvements in ISO-ES coupling coordination help reduce local CE. They also promote emission reductions in neighboring areas. This may be due to ecological network linkages, environmental policy diffusion, and regional resource flows. This finding to some extent complements the conclusion of Wang and Li (2024), who found that ISO exhibits spatial transmissibility, and the resulting experiences and policies have spatial spillover effects on CE in neighboring regions. It also extends the work of Li et al. (2024a), which examined the cross-regional externalities of improvements in ecosystem services. This study provides empirical evidence for the role of natural systems in environmental governance. In contrast to the traditional emphasis of ecological modernization theory on technological and industrial pathways, it highlights the importance of ES in green development, thereby enriching the theory's ecological dimension.

This study also finds that the negative impact of ISO-ES coupling coordination on CE weakens over time. This phenomenon echoes the law of diminishing marginal returns and the environmental Kuznets curve. It also reflects the practical constraints of industrial path dependence and spatial inertia. Similar conclusions have been reported by Ullah et al. (2023) and Liu and Guo (2025), who found that ecological policies tend to have higher marginal returns in the early stages but later rely on technological innovation and institutional upgrades to maintain effectiveness. Unlike previous studies (Schneiter and Mellon, 2025), this paper is the first to apply the principle of diminishing marginal returns to the context of ISO-ES coupling coordination. By adopting a dynamic perspective, it empirically verifies the time-varying nature of its carbon mitigation effects, thereby extending the theoretical applicability of this principle to the field of regional environmental governance.

In terms of methodology, previous studies mainly relied on OLS and SDM (Liu et al., 2024a; Liu and Chen, 2025). However, CE exhibit strong temporal dependence due to the inertia of production structures (Wang and Shao, 2024). In addition, the ISO-ES relationship is inherently long-term and involves substantial spatial spillovers shaped by regional ecological policies and interregional resource flows. Traditional OLS models fail to capture interregional spatial interactions, while SDM models overlook the dynamic inertia of carbon emissions (Meng et al., 2025). To address these limitations, this study introduces the DSDM and compares the regression results across models. We find that the magnitude of the ISO-ES coefficient increases as model control improves. This trend results from the structural improvements of the DSDM. This result is broadly in line with the findings of Alharbey and Ben-Salha (2024), who suggest that incorporating a time-lagged dependent variable helps to control for the dynamic inertia of carbon emissions and improves the distinction between local direct and spatial spillover effects. Consequently, the DSDM allows for a more accurate identification of the actual net effect of ISO-ES coupling coordination. This study thus extends the methodological applicability of DSDM in regional emission reduction.

6. Conclusion and implications

6.1. Conclusion

Using data from the YRB within the 2011 to 2023 period, this study has established the spatiotemporal evolution trends and relationships between ISO-ES coupling coordination and CE. The findings indicate stable and substantial advancement in coordinated ISO-ES in the region and slower CE growth. Nevertheless, emissions have increased significantly in some cities, placing greater pressure on the YRB to control its CE levels. This study has also revealed that ISO-ES coupling coordination alleviates CE, albeit with a weakening influence over time. The coordination between these sub-systems was also found to have a more substantial indirect effect on CE, underscoring significant spatial spillover. This indicates that efforts to promote ISO-ES coupling coordination in the YRB have significantly reduced emissions in surrounding areas, serving as a sound benchmark. Finally, the heterogeneity analysis indicates that the negative impact of ISO-ES coupling coordination on CE exhibits monotonic convergence from upstream to downstream regions. Efforts to couple ES with ISO have the most pronounced carbon-reducing effects in the upstream and midstream areas of the YRB. Future research could explore the mechanisms and moderating effects underlying the relationship between ISO-ES coupling coordination and carbon emissions and extend the scope of analysis to other regions.

6.2. Implications

In response to the continued rise in CE in key upstream cities such as Lanzhou and Xining, local governments are advised to develop differentiated and phased emission reduction strategies. These strategies need to coordinate the ISO with the enhancement of ES. Specifically, Local ecological and environmental departments should develop a green renovation catalogue for high-energy-consuming industries based on national or provincial green manufacturing standards, clearly classifying industry categories and process standards. In sectors such as steel and petrochemicals, adopting energy-saving equipment and technologies is encouraged to reduce CE through green loan interest subsidies and fiscal rewards. In parallel, projects for vegetation restoration, delineating water conservation areas, and constructing ecological buffer zones should be implemented. To enhance accountability, a carbon sink enhancement list must be established, with implementation carried out via carbon sink cooperatives or corporate carbon neutrality commitments.

Second, this study reveals that ISO-ES coupling coordination exerts a spatial spillover effect on carbon emissions, indicating the need for a unified cross-regional governance response. The central government should lead the establishment of a unified Eco-Industrial Coordination Platform for the YRB. This platform should serve as a cross-regional governance mechanism. It should coordinate carbon reduction tasks, allocate ecological resources across regions, facilitate green technology diffusion, and support joint project implementation. To ensure effectiveness, the platform can be built upon existing bodies such as the YRB ecological protection office, and leverage national high-tech zones or green industry parks as pilot nodes for technology dissemination. The platform construction should rely on central fiscal support and local financial matching. Special attention must be paid to regional disparities, weak technological absorption capacities, and administrative coordination obstacles in the process. It is recommended that training bases be built, fiscal transfer mechanisms be created, and government-business cooperation platforms be established to enhance the platform's effectiveness. These measures can help strengthen regional green transition capacities and reduce development gaps.

Third, since the emission reduction effects of ISO-ES coupling coordination weaken over time, policymakers should adopt differentiated and dynamic management approaches instead of uniform policies. Local governments should implement tailored incentive schemes. Regions with strong early-stage reduction performance but declining marginal effects can receive continued support through green tax exemptions or bond interest subsidies. Regions with lagging reduction progress should adopt green transition task lists to strengthen governance and promote industrial upgrading. Environmental authorities should establish real-time CE monitoring platforms in key regions and industries. A phased implementation strategy is advised, starting with the deployment of carbon monitoring and early warning systems in key industrial parks or high-emission zones, followed by broader application. These tools can help dynamically evaluate changes in coupling effects and improve policy response speed and precision.

Lastly, considering the heterogeneity in emission reduction potential across regions, a regional carbon trading platform based on total emission control should be established. The platform should be anchored in the national carbon market, implement a sub-regional quota allocation system, and be supported by a third-party accounting framework. The ISO-ES coupling coordination level should be incorporated as a key criterion for quota allocation to ensure the scientific determination of regional carbon emission limits. By establishing a carbon quota trading pool, the platform can guide the optimal cross-regional allocation of carbon resources. Upstream regions with strong emission reduction performance are allocated more transferable quotas and gain financial returns through trading. Downstream high-emission regions promote green transformation through quota purchases and fiscal subsidies, fostering a virtuous cycle of coordinated emission reduction between upstream and downstream areas.

6.3. Limitations and future directions

Although this study confirms the dynamic impact of ISO-ES coupling coordination on CE, the underlying mechanisms remain insufficiently explored. Future research could add mediating variables such as green credit, technological innovation capacity, and resource allocation efficiency to reveal the institutional, technological, and resource-based pathways. In addition, factors such as local governance capacity, market openness, and the stringency of environmental regulations may moderate the relationship between ISO-ES coupling coordination and CE. These moderating effects could be studied by including interaction terms in future analyses. Moreover, future studies are encouraged to broaden the research scope to other basins or regions. Particular attention could be given to areas with intensive economic and ecological interactions, such as the Yangtze River Basin. Comparative analyses across regions would further enhance the findings' external validity and policy relevance.

CRediT authorship contribution statement

Ruixiang Xue: Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Runde Gu:** Writing – review & editing, Methodology, Investigation, Funding acquisition, Conceptualization. **Tzesan Ong:** Writing – original draft, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This work received funding through Universiti Putra Malaysia (grant numbers: GP-GPB/2022/9716300); Science and Technology Program Projects of Hebei Academy of Sciences (grant numbers: 25B102).

Data availability

Data will be made available on request.

References

Abbass, K., Voinea, C.L., Roijakkers, N., Usman, M., Song, H., 2025. Innovation strategies for ecological sustainability: effects of natural resources and energy consumption. Sustain. Dev. (Bradf.). https://doi.org/10.1002/sd.3287.

Alharbey, M., Ben-Salha, O., 2024. Do institutions contribute to environmental sustainability? A global analysis using the dynamic spatial durbin and threshold models. J. Environ. Manag. 357, 120681. https://doi.org/10.1016/j.jenvman.2024.120681.

Ariken, M., Zhang, F., weng Chan, N., 2021. Coupling coordination analysis and spatio-temporal heterogeneity between urbanization and eco-environment along the silk road economic belt in China. Ecol. Indic. 121, 107014. https://doi.org/10.1016/j.ecolind.2020.107014.

Bai, T., Qi, Y., Li, Z., Xu, D., 2023. Digital economy, industrial transformation and upgrading, and spatial transfer of carbon emissions: the paths for low-carbon transformation of Chinese cities. J. Environ. Manag. 344, 118528. https://doi.org/10.1016/j.jenvman.2023.118528.

Bello-Pintado, A., Machuca, J.A., Danese, P., 2023. Stakeholder pressures and sustainability practices in manufacturing: consideration of the economic development context. Bus. Strat. Environ. 32 (7), 4084–4102. https://doi.org/10.1002/bse.3355.

Cabrera, D., Cabrera, L., 2023. What is systems thinking?. In: Learning, Design, and Technology: an International Compendium of Theory, Research, Practice, and Policy. Springer International Publishing, Cham, pp. 1495–1522. https://doi.org/10.1007/978-3-319-17461-7_100.

Capriolo, A., Boschetto, R.G., Mascolo, R.A., Balbi, S., Villa, F.J.E.S., 2020. Biophysical and economic assessment of four ecosystem services for natural capital accounting in Italy. Ecosyst. Serv. 46, 101207. https://doi.org/10.1016/j.ecoser.2020.101207.

Chen, D., Wang, Y., Bao, H., 2024. Sharing or sparing? The trade-offs among urban services, food production and ecosystem services. Habitat Int. 147, 103037. https://doi.org/10.1016/j.habitatint.2024.103037.

Chen, J., Gao, M., Cheng, S., Hou, W., Song, M., Liu, X., et al., 2020. County-level CO2 emissions and sequestration in China during 1997–2017. Sci. Data 7 (1), 391. https://doi.org/10.6084/m9.figshare.13090370.

Cheng, Y., Geng, X., Tian, W., 2025. Achieving low-carbon production: impacts of land misallocation and industrial structure in urban China. Appl. Energy 378, 124791. https://doi.org/10.1016/j.apenergy.2024.124791.

Costanza, R., 2020. Valuing natural capital and ecosystem services toward the goals of efficiency, fairness, and sustainability. Ecosyst. Serv. 43, 101096. https://doi.org/10.1016/j.ecoser.2020.101096.

Ding, J., Eldridge, D., 2024. Intensifying aridity induces tradeoffs among biodiversity and ecosystem services supported by trees. Global Ecol. Biogeogr., e13894 https://doi.org/10.1111/geb.13894.

Du, Z., Cui, H., Yan, F., Wang, L., Wei, Z., Hu, W., et al., 2025. CH4 and CO2 emissions and dissolved carbon exporting in rivers on the upper Lanzhou section of the Yellow River, China. Geosci. Front., 102057 https://doi.org/10.1016/j.gsf.2025.102057.

Feng, Y., Liu, W., Zhang, H., Li, Q., Zhu, A., 2024. Synergistic assessment of environmental pollutants and carbon emissions in the Yellow River Basin, China: an integrated study based on scenario simulation and process decomposition. Ecol. Indic. 166, 112334. https://doi.org/10.1016/j.ecolind.2023.112334.

Gong, M., Zeng, Y., Zhang, F., 2023. New infrastructure, optimization of resource allocation and upgrading of industrial structure. Finance Res. Lett. 54, 103754. https://doi.org/10.1016/j.frl.2023.103754.

Goulder, L.H., Kennedy, D., 2011. Interpreting and estimating the value of ecosystem services. Natural Cap.: Theor. Pract. Map. Ecosyst. Serv. 15. https://doi.org/10.1093/acprof:oso/9780199588992.003.0002.

Guo, S., Li, L., Wang, S., Huang, J., Xie, X., Wang, Y., 2024. What are the dominant drivers and optimal thresholds for a healthy ecosystem in the Yellow River Basin, China? From a perspective of nonlinear nexus. Ecol. Indic. 162, 111997. https://doi.org/10.1016/j.ecolind.2024.111997.

Hao, X., Li, Y., Ren, S., Wu, H., Hao, Y., 2023. The role of digitalization on green economic growth: does industrial structure optimization and green innovation matter? J. Environ. Manag. 325, 116504. https://doi.org/10.1016/j.jenvman.2022.116504.

Huang, Y., Zhang, S., Zhang, J., Fan, F., Zheng, H., 2025. Exploration of ecosystem asset-economy coupling coordination and its endogenous and exogenous drivers in mountainous regions. J. Clean. Prod. 486, 144460. https://doi.org/10.1016/j.jclepro.2024.144460.

Huerta de Soto, J., 2024. The law of diminishing marginal returns or productivity. In: Lectures in Austrian Economics, Volume I: Human Action, Competition Theory, Entrepreneurship, and Price Theory. Springer Nature Switzerland, Cham, pp. 193–198. https://doi.org/10.1007/978-3-031-63886-2_20.

Huo, W., Qi, J., Yang, T., Liu, J., Liu, M., Zhou, Z., 2022. Effects of China's pilot low-carbon city policy on carbon emission reduction: a quasi-natural experiment based on satellite data. Technol. Forecast. Soc. Change 175, 121422. https://doi.org/10.1016/j.techfore.2021.121422.

Jing, X., Tian, G., He, Y., Wang, M., 2024. Spatial and temporal differentiation and coupling analysis of land use change and ecosystem service value in Jiangsu Province. Ecol. Indic. 163, 112076. https://doi.org/10.1016/j.ecolind.2024.112076.

Kpienbaareh, D., Kerr, R.B., Nyantakyi-Frimpong, H., Iverson, A., Luginaah, I., Lupafya, E., et al., 2024. Ecosystem service demand and supply dynamics under different farming systems: a participatory GIS assessment in Malawi. Appl. Geogr. 171, 103372. https://doi.org/10.1016/j.apgeog.2023.103372.

Laszlo, E., 2024. System, Structure and Experience: toward a Scientific Theory of Mind. Routledge. https://doi.org/10.4324/9781003507727.

Li, N., Sun, P., Zhang, J., Mo, J., Wang, K., 2024a. Spatiotemporal evolution and driving factors of ecosystem services' transformation in the Yellow River basin, China. Environ. Monit. Assess. 196 (3), 252. https://doi.org/10.1007/s10661-024-11495-3.

Li, S., Xiang, N., Shu, C., Xu, F., 2025. Unveiling the industrial synergy optimization pathways in Beijing-Tianjin-Hebei urban agglomeration based on water-energy-carbon nexus. J. Environ. Manag. 376, 124528. https://doi.org/10.1016/j.jenvman.2025.124528.

Li, T., Li, D., Liu, Y., Wei, G., Liu, C., Wang, J., 2024b. The spatiotemporal effects on ecosystem services supply-demand from industrial transformation and upgrading: promotion or inhibition? Ecol. Indic. 161, 111990. https://doi.org/10.1016/j.ecolind.2023.111990.

Lin, C., Liu, J., Li, W., 2023. Influence of the high-speed railway (HSR) construction on industrial structure transformation. Enterp. Inf. Syst. 17 (2), 1942998. https://doi.org/10.1080/17517575.2023.1942998.

Liu, L., Zhang, L., Li, B., Wang, Y., Wang, M., 2024a. Can financial agglomeration curb carbon emissions reduction from agricultural sector in China? Analyzing the role of industrial structure and digital finance. J. Clean. Prod. 440, 140862. https://doi.org/10.1016/j.jclepro.2023.140862.

Liu, P., Zhu, B., 2022. Temporal-spatial evolution of green total factor productivity in China's coastal cities under carbon emission constraints. Sustain. Cities Soc. 87, 104231. https://doi.org/10.1016/j.scs.2022.104231.

Liu, W., Chen, X., 2025. Evaluating the impact of energy efficiency on green growth in Chinese cities: a spatial durbin model approach. Energy (Calg.) 322, 135298. https://doi.org/10.1016/j.energy.2025.135298.

Liu, X., Guo, W., 2025. Dynamic impact of green finance on renewable energy development: based on scale, structure, and efficiency perspectives. Renew. Energy 238, 121854. https://doi.org/10.1016/j.renene.2024.121854.

Liu, Z., Chang, Y., Pan, S., Zhang, P., Tian, L., Chen, Z., 2024b. Unfolding the spatial spillover effect of urbanization on composite ecosystem services: a case study in cities of Yellow River Basin. Ecol. Indic. 158, 111521. https://doi.org/10.1016/j.ecolind.2023.111521.

Liu, Z., Wu, R., Chen, Y., Fang, C., Wang, S., 2021. Factors of ecosystem service values in a fast-developing region in China: insights from the joint impacts of human activities and natural conditions. J. Clean. Prod. 297, 126588. https://doi.org/10.1016/j.jclepro.2021.126588.

Ma, Z., Zhang, P., 2025. Myth of the digital economy: can it continually contribute to a low-carbon status and sustainable development? Environ. Impact Assess. Rev. 110, 107688. https://doi.org/10.1016/j.eiar.2024.107688.

Meng, Y., Zhang, Y., Hou, Z., Zhang, X., Liu, F., 2025. Niche fitness of digital innovation ecosystems: evaluation, dynamic evolution and spatial effects. Eur. J. Innovat. Manag. https://doi.org/10.1108/EJIM-10-2024-1211.

Muhammad, S., Pan, Y., Agha, M.H., Umar, M., Chen, S., 2022. Industrial structure, energy intensity and environmental efficiency across developed and developing economies: the intermediary role of primary, secondary and tertiary industry. Energy (Calg.) 247, 123576. https://doi.org/10.1016/j.energy.2022.123576.

Pan, H., Du, Z., Wu, Z., Zhang, H., Ma, K., 2024. Assessing the coupling coordination dynamics between land use intensity and ecosystem services in Shanxi's coalfields, China. Ecol. Indic. 158, 111321. https://doi.org/10.1016/j.ecolind.2023.111321.

Pea-Assounga, J.B.B., Bambi, P.D.R., Jafarzadeh, E., Ngapey, J.D.N., 2025. Investigating the impact of crude oil prices, CO2 emissions, renewable energy, population growth, trade openness, and FDI on sustainable economic growth. Renew. Energy 241, 122353. https://doi.org/10.1016/j.renene.2025.122353.

Qu, H., You, C., Feng, C.C., Guo, L., 2024. Spatial responses of ecosystem services to carbon emission efficiency based on spatial panel models in the Yangtze River Economic belt. J. Clean. Prod. 434, 139953. https://doi.org/10.1016/j.jclepro.2023.139953.

Rong, T., Zhang, P., Li, G., Wang, Q., Zheng, H., Chang, Y., Zhang, Y., 2023. Spatial correlation evolution and prediction scenario of land use carbon emissions in the Yellow River Basin. Ecol. Indic. 154, 110701. https://doi.org/10.1016/j.ecolind.2023.110701.

Schneiter, P., Mellon-Bedi, S., 2025. The environmental kuznets curve revisited: a spatial panel model with heterogeneous coefficients. Energy Econ. 143, 108237. https://doi.org/10.1016/j.eneco.2025.108237.

Shi, Y., Guan, Y., Li, L., Huang, M., 2022. Empirical analysis on the impacts of carbon sink afforestation project on county industrial structural upgrading. Alex. Eng. J. 61 (1), 207–216. https://doi.org/10.1016/j.aej.2021.11.013.

Song, M., An, M., He, W., Wu, Y., 2025. Research on land use optimization based on PSO-GA model with the goals of increasing economic benefits and ecosystem services value. Sustain. Cities Soc. 119, 106072. https://doi.org/10.1016/j.scs.2024.106072.

Sun, Y., Liu, S., Dong, Y., An, Y., Shi, F., Dong, S., Liu, G., 2019. Spatio-temporal evolution scenarios and the coupling analysis of ecosystem services with land use change in China. Sci. Total Environ. 681, 211–225. https://doi.org/10.1016/j.scitotenv.2019.05.136.

Tao, M., Poletti, S., Wen, L., Sheng, M.S., 2024. Modelling the role of industrial structure adjustment on China's energy efficiency: insights from technology innovation. J. Clean. Prod. 441, 140861. https://doi.org/10.1016/j.jclepro.2023.140861.

Ullah, S., Luo, R., Adebayo, T.S., Kartal, M.T., 2023. Dynamics between environmental taxes and ecological sustainability: evidence from top-seven green economies by novel quantile approaches. Sustain. Dev. (Bradf.) 31 (2), 825–839. https://doi.org/10.1002/sd.2423.

Wang, H., Zhan, J., Wang, C., Chen, B., Yang, Z., Bai, C., 2024. Short-term fluctuations of ecosystem services beneath long-term trends. Resour. Conserv. Recycl. 203, 107454. https://doi.org/10.1016/j.resconrec.2024.107454.

Wang, L., Zheng, H., Chen, Y., Ouyang, Z., Hu, X., 2022. Systematic review of ecosystem services flow measurement: main concepts, methods, applications and future directions. Ecosyst. Serv. 58, 101479. https://doi.org/10.1016/j.ecoser.2022.101479.

Wang, Y., Li, L., 2024. Digital economy, industrial structure upgrading, and residents' consumption: empirical evidence from prefecture-level cities in China. Int. Rev. Econ. Finance 92, 1045–1058. https://doi.org/10.1016/j.iref.2023.10.012.

Wang, Z., Shao, H., 2024. Spatiotemporal interactions and influencing factors for carbon emission efficiency of cities in the Yangtze River Economic Belt, China. Sustain. Cities Soc. 103, 105248. https://doi.org/10.1016/j.scs.2024.105248.

Wei, W., Chen, D., Zhang, X., Ma, L., Xie, B., Zhou, J., et al., 2024. Estimation of carbon emissions from different industrial categories integrated nighttime light and POI data—A case study in the Yellow River Basin. J. Environ. Manag. 370, 122418. https://doi.org/10.1016/j.jenvman.2023.122418.

Wen, L., Li, B., Peng, Y., Zhou, Y., Weng, A., Jin, Y., et al., 2024. Exploring the evolution of coupled natural-cultural ecosystem services and their geographically scaled driven modeling in a coastal city of Southeast China. J. Environ. Manag. 361, 121265. https://doi.org/10.1016/j.jenvman.2024.121265.

Wu, D., Zhou, D., Zhu, Q., Wu, L., 2023. Industrial structure optimization under the rigid constraint of carbon peak in 2030: a perspective from industrial sectors. Environ. Impact Assess. Rev. 101, 107140. https://doi.org/10.1016/j.eiar.2023.107140.

Xia, Y., Shi, J., Zhao, Z., Liu, Z., Liu, X., Zhang, C., 2023. Mapping the coal-water nexus in the Yellow River Basin. J. Clean. Prod. 411, 137249. https://doi.org/10.1016/j.jclepro.2023.137249.

Xue, R., Ong, T.S., Demir, E., 2024. Do CEO and chairman characteristics affect green innovation? Evidence from a comparative analysis of machine learning models. Environ. Dev. Sustain. 1–28. https://doi.org/10.1007/s10668-023-03600-0.

Yan, Y., Yang, Y., Yang, M., 2024. Unravelling the non-linear response of ecosystem services to urban-rural transformation in the Beijing-Tianjin-Hebei region, China. Ecol. Inform. 81, 102633. https://doi.org/10.1016/j.ecoinf.2023.102633.

Yuan, D., Du, M., Yan, C., Wang, J., Wang, C., Zhu, Y., et al., 2024. Coupling coordination degree analysis and spatiotemporal heterogeneity between water ecosystem service value and water system in Yellow River Basin cities. Ecol. Inform. 79, 102440. https://doi.org/10.1016/j.ecoinf.2023.102440.

Zhang, Z., Hua, C., Jiang, M.S., Miao, J., 2024. The spatial spillover effect of financial growth on high-quality development: evidence from Yellow River Basin in China. Humanit. Soc. Sci. Commun. 11 (1), 1–17. https://doi.org/10.1057/s41599-023-01600-0.

Zhao, X., Shang, Y., Song, M., 2020. Industrial structure distortion and urban ecological efficiency from the perspective of green entrepreneurial ecosystems. Soc. Econ. Plann. Sci. 72, 100757. https://doi.org/10.1016/j.seps.2020.100757.

Zhong, L., Lin, Y., Yang, M., He, Y., Liu, X., Yu, P., Xie, Z., 2025. Spatiotemporal pattern of embodied carbon emissions from in-use steel stock in countries along the Belt and Road. Resour. Conserv. Recycl. 214, 108038. https://doi.org/10.1016/j.resconrec.2024.108038.