Ecological Indicators 173 (2025) 113423

Contents lists available at ScienceDirect

Ecological Indicators

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

Original Articles

From regional imbalances to latecomer advantage: Phosphorus pollution and economic development in the Yangtze economic belt

Jincheng Li [a,b], Xinyue Zhang [c,d], Taher Kahil [b], Dongni Chen [e], Guangyao Wang [f], Shasha Xu [g], Yang Zhang [a,h,*], Yan Chen [h,*]

[a] College of Environmental Sciences and Engineering, State Environmental Protection Key Laboratory of All Material Fluxes in River Ecosystems, Peking University, Beijing, China
[b] Water Security Research Group, Biodiversity and Natural Resources Program, International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria
[c] State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin, Beijing, China
[d] China Institute of Water Resources and Hydropower Research (IWHR), Beijing, China
[e] Yunnan Academy of Ecological and Environmental Sciences, Kunming, China
[f] College of Water Resources and Architectural Engineering, Northwest A & F University, Yangling, China
[g] Henan Provincial Key Laboratory of Hydrosphere and Watershed Water Security, North China University of Water Resources and Electric Power, Zhengzhou, China
[h] Chinese Academy of Environmental Planning, Beijing, China

ARTICLE INFO

Keywords:
Net anthropogenic phosphorus input
Environmental Kuznets curve
Yangtze River economic belt
Phosphorus management and sustainability
Economic development and environmental impact

ABSTRACT

Phosphorus pollution from human activities threatens ecosystems, especially in rapidly developing regions. This study aims to assess the spatiotemporal dynamics of net anthropogenic phosphorus input (NAPI) in the Yangtze River Economic Belt (YREB) from 1980 to 2020, focusing on the balance between economic growth and environmental sustainability. Employing the Logarithmic Mean Divisia Index (LMDI) and Environmental Kuznets Curve (EKC) frameworks, the study identifies two key inflection points in the NAPI-GDP per capita relationship, marking shifts in phosphorus input trends. Results indicate that NAPI in the YREB increased significantly from 1980 to 2020, mainly due to fertilizer application (62.36%) and economic growth (77.8%). Regional disparities persist: the eastern region reached its EKC turning point earlier, while the western region benefited a "latecomer advantage," achieving reductions at a lower economic threshold. By 2020, most YREB regions had crossed their EKC turning points, signaling a transition to coordinated economic and environmental progress. Policies such as the "Ten Water Regulations" significantly reduced phosphorus inputs, particularly in high-pollution areas. Continued investment in sustainable agricultural practices, green technology, and targeted regional strategies is essential to bridge phosphorus management gaps. The findings provide critical insights into phosphorus pollution dynamics in a major economic corridor and demonstrates a replicable framework for integrating environmental considerations into economic planning. These results contribute to developing actionable strategies for cleaner production and long-term sustainability in rapidly developing regions.

1. Introduction

Phosphorus is essential for sustaining life and plays a fundamental role in agricultural production and economic activities. However, rapid economic growth, intensive fertilizer use, and urbanization have led to excessive phosphorus inputs into river basins. This has led to eutrophication and the degradation of aquatic ecosystems, which have become pressing global concerns (Diamond and Wang, 2024; Wu et al., 2022). To reconcile economic growth with environmental sustainability, China has launched initiatives such as the Beautiful China Initiative (BCI), aimed at fostering sustainable development (Qin et al., 2023; Qin et al., 2024). These interventions align with global efforts under the United Nations Sustainable Development Goals (SDGs), particularly SDG 6 (Clean Water and Sanitation) and SDG 12 (Responsible Consumption and Production). Nonetheless, the effectiveness of these measures in achieving regional economic-environmental balance remains insufficiently evaluated. Most previous studies on phosphorus pollution have focused on basin-wide or provincial scales, lacking high-resolution temporal and spatial insights at the prefectural level. Given that the Yangtze River Economic Belt accounts for over 40 % of China's economy

* Corresponding authors.
E-mail addresses: zhangyang2019@pku.edu.cn (Y. Zhang), chenyan@caep.org.cn (Y. Chen).

https://doi.org/10.1016/j.ecolind.2025.113423
Received 4 February 2025; Received in revised form 27 March 2025; Accepted 28 March 2025
Available online 4 April 2025

and population, a detailed analysis of its phosphorus pollution trends is essential for sustainable management.

Understanding the relationship between phosphorus pollution in river basins and economic growth is fundamental for devising effective measures to mitigate environmental degradation driven by economic development. The EKC framework provides a theoretical basis for analyzing this relationship. It is typically represented as an inverted U-shape, where pollution levels initially rise with economic growth due to increased industrial and agricultural activities, but beyond a critical economic threshold, technological advancements, policy interventions, and structural shifts toward a service-oriented economy lead to pollution reductions (Durmaz and Thompson, 2024; Shen et al., 2023). The EKC hypothesis suggests that economic growth, once past a specific turning point, can contribute positively to environmental quality by promoting cleaner production methods and more efficient resource management (Ahmad et al., 2021; Zhu et al., 2022). In the context of phosphorus pollution, this turning point is influenced by factors such as advancements in fertilizer use efficiency, wastewater treatment infrastructure, and the implementation of stricter environmental regulations (Farooq et al., 2024; Guo and Shahbaz, 2024). Evaluating whether the long-term relationship between economic growth and phosphorus pollution has surpassed this threshold is crucial for assessing sustainability, especially in economically underdeveloped regions (Aminu et al., 2023; Lin et al., 2016). Numerous models have been developed to evaluate phosphorus pollution levels, with the NAPI model being extensively utilized across different scales due to its simplicity and ease of parameter acquisition (Wang et al., 2020; Zhong et al., 2022). First introduced in 2008, the NAPI model quantifies phosphorus input intensity driven by human activities within river basins (Russell et al., 2008). The model disaggregates anthropogenic phosphorus inputs into three main components: fertilizer application, net input from regional food trade, and non-food inputs, representing the primary phosphorus sources linked to human activities (Wang et al., 2023c; Yang et al., 2023). Enhanced versions of the NAPI model have been extensively applied to assess phosphorus input cycles, identify driving forces, and analyze structural changes across regions in the Americas, Europe, and Asia (Houssini et al., 2023; Van Staden et al., 2022). The Yangtze River Economic Belt encompasses both the economically underdeveloped western region and the developed eastern region of China. However, long-term evaluations of the relationship between anthropogenic phosphorus inputs and economic growth in this region remain scarce. This knowledge gap hinders our understanding to determine whether different regions within the belt have surpassed the EKC threshold.

The Yangtze River Economic Belt (YREB) is a critical region for China's economic development, facing the significant challenge of achieving high-quality growth that harmonizes economic expansion with environmental sustainability. Accounts for over 20 % of China's land area, 43 % of its population, and 45 % of its GDP, the YERB is also responsible for more than 40 % of the nation's pollutant emissions (Yang and Ran, 2024; Zheng et al., 2024). Spanning from the environmentally fragile and economically underdeveloped Qinghai-Tibet Plateau to the economically advanced and densely urbanized Yangtze River Delta, the Yangtze River—the longest river in China—plays a pivotal role in both the environment and the economy (Guan et al., 2024; Wang et al., 2023a). Since 1980, phosphorus inputs in the region have exhibited a significant upward trend, increasing by an average of 2300 tons annually through 2015, with over 30 % of phosphorus pollution attributed to industrial and agricultural sources (Huang et al., 2024; Zhao et al., 2022). National surface water quality monitoring reveals that more than 10 % of the Yangtze River's monitored sections fall into Category IV, with phosphorus identified as the primary pollutant (Wang et al., 2024). This growing pressure on aquatic environments has severely disrupted ecosystems, with algal blooms occurring with increasing frequency (Guan et al., 2020; Liu et al., 2024). China's regional development strategy, which prioritizes the eastern region, combined with natural variations, has resulted in significant disparities in economic structures and phosphorus emissions across the Yangtze River Economic Belt (Liu et al., 2022; Zhang et al., 2021). In the western region, environmental degradation has often been traded for economic growth, exacerbating the imbalance between development and environmental sustainability. Existing studies on phosphorus inputs in the Yangtze River Economic Belt primarily focused on basin, provincial, or national scales, with a lack of long-term analyses at the prefectural level (Deng et al., 2021; Liu et al., 2022). This research gap hinders the ability to capture the region's characteristics and heterogeneity of phosphorus pollution, and it limits the integration of economic development indicators needed to assess the imbalance between regional development and environmental protection. Therefore, studies at the prefectural level, employing long-term datasets on phosphorus inputs and economic growth, are urgently needed to uncover the evolving disparities between economic expansion and environmental sustainability in the YREB.

To address the absence of long-term analyses at the prefectural level on the evolving relationship between economic development and pollution levels in the Yangtze River Economic Belt, this study develops a NAPI model for prefectural-level cities in the region spanning 1980 to 2020 and seeks to answer three key questions: (1) How have net anthropogenic phosphorus inputs evolved in the YREB over the past four decades? (2) What are the major drivers influencing phosphorus pollution trends in different regions? (3) How does phosphorus pollution relate to economic development, and have any turning points been observed in this relationship? Addressing these questions will provide a more comprehensive understanding of the balance between economic expansion and environmental sustainability in the YREB. This study contributes to the existing literature by integrating high-resolution spatial and temporal analyses to examine phosphorus input dynamics in the YREB. We employ a detailed prefectural-level dataset spanning four decades, allowing for more precise identification of regional disparities and driving forces behind phosphorus pollution. By incorporating the EKC framework, we also evaluate whether economic growth has led to reductions in phosphorus inputs across different regions.

2. Data and methodology

2.1. Study area

The Yangtze River Economic Belt (YREB) spans eastern, middle, and western China (21°08′–34°19′N, 97°31′–122°16′E), encompassing 11 provinces and 130 cities (Wang and Yang, 2025; Zheng et al., 2024). Contributing to over 40 % of China's total economy and population, the YREB serves as a crucial region for coordinated development through the interaction of its eastern, middle, and western regions. Additionally, it serves as a pioneering demonstration zone for ecological civilization and a strategic battleground for advancing eco-friendly and sustainable development. The region benefits from a warm climate, abundant rainfall, extensive vegetation cover, and robust ecosystem service capacity. However, rapid economic activities have imposed considerable pressure on the ecosystem, leading to significant environmental pollution. Based on administrative divisions, natural geography, and socio-economic development levels, the YREB is divided into three sub-regions: eastern, middle, and western (Fig. 1). The western region comprises Sichuan, Chongqing, Yunnan, and Guizhou Provinces. The middle region includes Jiangxi, Hubei, and Hunan Provinces, while the eastern region encompasses Shanghai, Jiangsu, Zhejiang, and Anhui Provinces.

2.2. Data sources

This study utilizes data from multiple statistical sources to estimate Net Anthropogenic Phosphorus Input for 130 prefecture-level cities in the Yangtze River Economic Belt from 1980 to 2020. Data on population size, crop sown area and yield, livestock and poultry production, and fertilizer application were obtained from the China Statistical Yearbook,

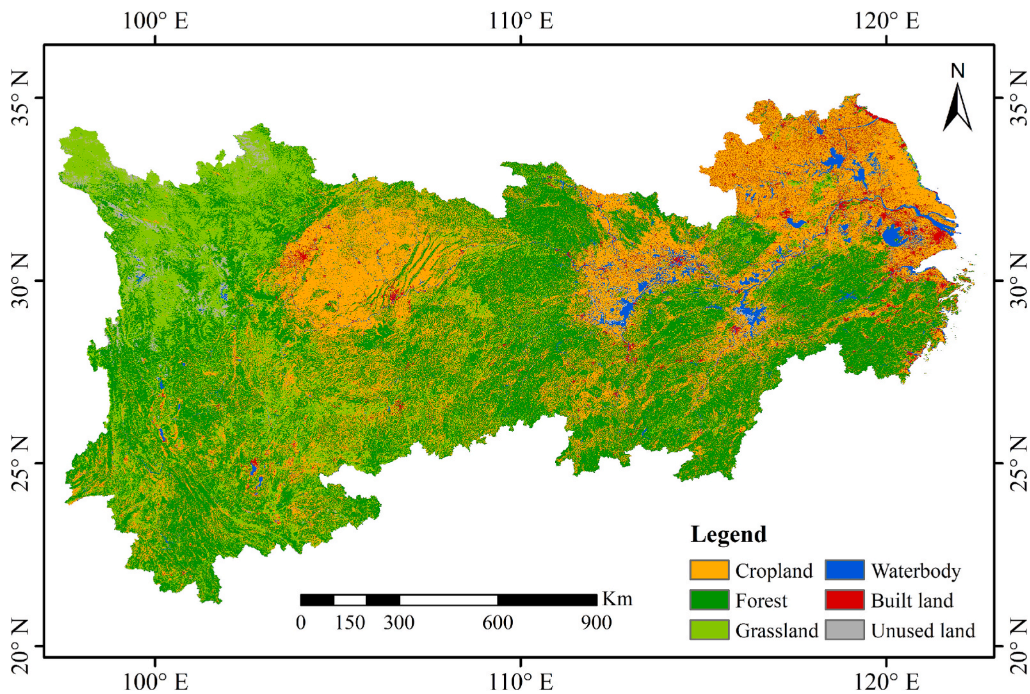

Fig. 1. Location and land use of the Yangtze River Economic Belt.

China City Statistical Yearbook, China Animal Husbandry and Veterinary Yearbook, China Rural Statistical Yearbook, and local statistical yearbooks for respective cities. Since prefecture-level cities data are systematically available only after 1990, earlier values for 1980 were reconstructed using proportional downscaling from provincial-level data, assuming the same intra-provincial distribution observed in 1990. To ensure data consistency, we performed cross-validation against provincial and national statistics using summation checks and volatility assessments. For instance, when reconstructing 1980s data, we verified that the sum of interpolated prefectural data aligned with corresponding provincial statistics. Additionally, we assessed historical trends in each variable to identify anomalies caused by statistical reporting adjustments. In cases where discrepancies arose due to administrative reclassifications, adjustments were made by averaging multi-year estimates to smooth inconsistencies. For years when direct prefectural-level statistics were unavailable (primarily before 1990), missing values were estimated using a combination of proportional downscaling, moving-average smoothing, and exponential regression models. Proportional downscaling was used to distribute provincial-level phosphorus input based on the relative shares of GDP, agricultural land area, and population observed in later years (e.g., 1990). A moving-average approach was applied to smooth out inconsistencies due to administrative boundary changes. In addition, exponential regression models were used to adjust historical urbanization rates, ensuring consistency with observed trends in later years. To validate the robustness of our phosphorus input estimates, we applied the following statistical validation methods: (1) Summation and Consistency Checks: We ensured that the sum of prefecture-level cities estimates aligned with official provincial statistics. Any deviations beyond ±5 % were re-evaluated. (2) Volatility Assessments: We examined year-over-year variations in phosphorus inputs to identify potential statistical anomalies due to administrative changes or shifts in data reporting practices. (3) Comparative Benchmarking: Our results were cross-compared with previously published phosphorus budgets in China (Wang et al., 2020; Zhao et al., 2022) to confirm that the estimated phosphorus inputs were within expected ranges. (4) Spatial Autocorrelation Analysis: We applied Global Moran's I tests to detect spatial clustering patterns in phosphorus inputs, ensuring that our model captured realistic spatial dependencies.

2.3. NAPI model

The NAPI model is developed using a material balance approach, quantifying human-induced phosphorus inputs at a regional scale. The model categorizes inputs into three primary components: (1) phosphorus application from fertilizer, (2) net phosphorus inputs from regional food and feed trade, and (3) non-food phosphorus sources, such as industrial and household products. All parameters are in $kg \cdot km^{-2} \cdot a^{-1}$ unless otherwise stated. The calculation formula is as follows:

$$NAPI = P_{fer} + P_{im} + P_{nf} \tag{1}$$

where *NAPI* is the net anthropogenic phosphorus input per unit area; P_{fer} is the phosphorus input of fertilizer application; P_{im} is the phosphorus input of food/feed; P_{nf} is the non-food phosphorus input.

2.3.1. Fertilizer application input

The amount of phosphorus inputs of phosphate fertilizers (*PF*) and compound fertilizers (*CF*) is calculated by standardizing their phosphorus content ($kg \cdot a^{-1}$). The calculation formula is as follows:

$$P_{fer} = (PF + CF \times Pr) \times 43.64\% / Area \tag{2}$$

where P_r is the percentage of P_2O_5 in compound fertilizers (35 %) (Ju et al., 2025), according to common fertilizer formulas in the Chinese market. Phosphate fertilizers are calculated as P_2O_5, where the phosphorus content in P_2O_5 is 43.64 %. *Area* is the region area (km^2).

2.3.2. Food/feed input

Food/feed input (P_{im}) refers to the difference between phosphorus intake and output of humans and livestock, reflecting the supply–demand balance. The calculation formula is:

$$P_{im} = P_{hc} + P_{lc} - P_{lp} - P_{cp} \tag{3}$$

where P_{hc} is the phosphorus content in food; P_{lc} is the phosphorus content in feed consumption; P_{lp} is the phosphorus content in livestock products (e.g., meat, eggs); P_{cp} is the phosphorus content in crop products.

$$Phc = (POP_{ub} \times IT_{ub} + POP_{rr} \times IT_{rr}) \times 365 \times 10^{-6} / Area \quad (4)$$

where POP_{ub} and POP_{rr} is the urban and rural population (people). IT_{ub} and IT_{rr} is the daily per capita phosphorus intake (mg·people^{-1}·day^{-1}). Coefficients were showed in Table S1.

$$Plc = \sum_{i=1}^{11} (LA_i \times IL_i) / Area \quad (5)$$

where LA is the livestock amount and IL is the intake coefficients, which were showed Table S2 (kg·head^{-1}·a^{-1}). i represents 11 species of livestock, including cattle, cow, pig, sheep, goat, horse, donkey, mule, camel, chicken, duck and goose.

$$Plp = \sum_{i=1}^{11} [LA_i \times (LI_i - LE_i) \times redi] / Area \quad (6)$$

where LI and LE is the phosphorus intake and excretion of livestock (kg·head^{-1}·a^{-1}). red is the edible proportion of livestock products (%), which were showed Table S2.

$$Pcp = \sum_{j=1}^{18} (CY_j \times PC_j \times 0.9) / Area \quad (7)$$

where CY is the yield of crops (kg) and PC is the phosphorus content (%). j is the crop species, which were showed Table S3. 10 % of the crop is not consumed by humans and livestock due to processing and transportation losses.

2.3.3. Non-food input

Non-food phosphorus input primarily refers to the use of various materials, products, and chemicals in daily life, such as pesticides, phosphorus-containing detergents, matches, and various fuels. The formula is:

$$P_{nf} = (POP \times PE \times 10^{-3}) / Area \quad (8)$$

where PE is the per capita non-food phosphorus input with 630 g·people^{-1}·a^{-1} (Gao et al., 2020).

2.4. Spatial analysis

Hotspot analysis is a spatial clustering method used to identify statistically significant high values (hot spots) and low values (cold spots). The principle involves analyzing the degree of clustering and confidence levels of elements within a dataset by weighting various factors differently. Unlike high/low clustering analysis, hot spot analysis does not necessarily have statistical significance but rather indicates that high values are more attractive compared to other elements in the dataset (Li et al., 2022; Li et al., 2023b). When hot spot analysis occurs locally, it carries statistical clustering significance. The Getis-Ord Gi* statistic is an essential indicator for measuring local spatial autocorrelation characteristics (Bruhn et al., 2023; Jaganathan et al., 2025). In this study, the hot spot analysis method was employed to calculate the Getis-Ord Gi* statistic for each element in the dataset, returning and analyzing the Z-scores (G_i*) of the Getis-Ord Gi* statistic. The formula as follows:

$$G_i^* = \frac{\sum_{j=1}^{n} \omega_{i,j} x_j - \overline{X} \sum_{j=1}^{n} \omega_{i,j}}{S \sqrt{\frac{\left[n \sum_{j=1}^{n} \omega_{i,j}^2 - \left(\sum_{j=1}^{n} \omega_{ij} \right)^2 \right]}{n-1}}} \quad (9)$$

where G_i^* represents the Z-score of the Getis-Ord G_i^* statistic; x_j denotes the attribute value of element j, typically representing attributes such as distance, area, or score; $\omega_{i,j}$ indicates the relative weight between elements i and j; $\overline{x}$ is the mean attribute value of the dataset; S is the standard deviation of the attributes; n is the total number of elements involved in the analysis.

2.5. Driving factors analysis

To enhance analytical depth, this study integrates the NAPI model with the Logarithmic Mean Divisia Index (LMDI) method and the Environmental Kuznets Curve (EKC) framework. The LMDI method is used to decompose contributions of driving factors to phosphorus input. A key advantage of this method is its ability to attribute contributions without leaving residual terms, making it widely used in fields such as greenhouse gas emissions and energy efficiency analysis (Alajmi, 2021; Wang et al., 2023b). The EKC framework is employed to investigate whether phosphorus pollution follows an inverted U-shaped trajectory as economic development progresses (Ahmad et al., 2021; Shen et al., 2023). Phosphorus input is closely linked to food consumption and production, which are influenced by socioeconomic development levels and industrial structures. Previous studies have demonstrated that the proportion of protein intake differs significantly between urban and rural residents and increases with rising income levels (Dalsgaard et al., 2023). Therefore, this study categorizes the driving forces of NAPI into four effects: population, economic level, industrial structure, and phosphorus input intensity effect. The decomposition identity is as follows:

$$NAPI = \sum_{i=1}^{2} \sum_{j=1}^{3} \left(POP_i \times \frac{GDP}{POP} \times \frac{GDP_j}{GDP} \times \frac{NAPI}{GDP} \right) \quad (10)$$

where POP represents the total population (i = 1: urban and 2: rural). GDP refers to the gross domestic product (j = 1: primary industries, 2: secondary industries, and 3: tertiary industries).

$$P_i = POP_i \quad (11)$$

$$GP = \frac{GDP}{POP} \quad (12)$$

$$G_j = \frac{GDP_j}{GDP} \quad (13)$$

$$PG = \frac{NAPI}{GDP} \quad (14)$$

$$\Delta NAPI = NAPI^F - NAPI^I = \sum_{i=1}^{2} \Delta P_i + \Delta GP + \sum_{j=1}^{3} \Delta G_j + \Delta PG \quad (15)$$

where $NAPI^I$ and $NAPI^F$ are the initial and final NAPI, P, GP, G and PG is the population, economic level, industrial structure, and phosphorus input intensity effect, respectively. Based on the LMDI model, the above formula is decomposed to derive the calculation formula for each factor:

$$t = \frac{NAPI^F - NAPI^I}{\sum_{i=1}^{2} \sum_{j=1}^{3} (\ln(P_i^F \times GP^F \times G_j^F \times PG^F) - \ln(P_i^I \times GP^I \times G_j^I \times PG^I))} \quad (16)$$

$$\Delta P_i = t \times \ln \frac{P_i^F}{P_i^I} \times I \quad (17)$$

$$\Delta GP = t \times \ln \frac{GP^F}{GP^I} \times I \times J$$

$$\Delta G_j = t \times \ln \frac{G_j^F}{G_j^I} \times J \quad (19)$$

$$\Delta PG = t \times \ln \frac{PG^F}{PG^I} \times I \times J \quad (20)$$

where I and J represent the total number of population and industrial structure types, respectively ($I = 2$ and $J = 3$).

3. Results and discussion

3.1. NAPI trends and regional differences

Net anthropogenic phosphorus input (NAPI) in the Yangtze River Economic Belt (YREB) has surpassed its historical growth inflection point, evolving over the past forty years through three distinct phases. Between 1980 and 2020, NAPI increased from 649.23 to 1525.12 kg/(km^2 a), representing a 2.35-fold rise, with an average annual growth of 21.90 kg/(km^2 a) (Fig. 2a). Compared to the national average of 840.13 kg/(km^2 a) in 2020, NAPI in the YREB was 2.24 times higher, underscoring the urgent need to address phosphorus pollution within the region ((Fu et al., 2024)). The entire period can be categorized into three phases: rapid growth, steady transition, and gradual decline. Phase I: Rapid Growth (1980–2005). During this period, NAPI in the YREB increased sharply, rising by 2.47 times with an average annual increase of 36.76 kg/(km^2 a). This phase coincided with China's implementation of five consecutive Five-Year Plans, resulting in a 5.12-fold GDP growth and a 1.33-fold population increase. National policies prioritized economic expansion, often at the expense of environmental protection, to alleviate poverty and sustain growth (Wang and Feng, 2021). Consequently, phosphorus pollution in the YREB surged significantly. Phase II: Steady Transition (2006–2015). In this phase, NAPI growth stabilized, increasing by 9.97 % with an average annual growth of 20.01 kg/(km^2 a). Binding targets for major pollutant reductions were introduced during the 11th Five-Year Plan, including a mandated 10 % reduction in key pollutants (Liao and Zhang, 2024). The 12th Five-Year Plan emphasized green development initiatives, effectively mitigating the worsening trend of environmental pollution alongside economic growth, particularly in the downstream YREB (Lin et al., 2023). Phase III: Gradual Decline (2015–2020). A gradual reduction in NAPI was observed during this phase, with levels decreasing by 13.59 % and an average annual reduction of 39.99 kg/(km^2·a). The 13th Five-Year Plan marked the implementation of ecological civilization strategies, featuring stricter environmental regulations, green technology innovation, and comprehensive control of agricultural non-point source pollution (Ji et al., 2023). As a result, phosphorus pollution across the YREB was effectively managed and reduced. At the same time, economic structural adjustments contributed to phosphorus reductions. The agricultural sector saw a transition toward precision farming and reduced chemical fertilizer dependency, while industrial restructuring led to the decline of high-phosphorus-emitting industries in favor of cleaner production. The LMDI decomposition analysis (Fig. 5a) suggests that while economic development contributed 77.8 % to overall phosphorus input trends, signaling the impact of policy-driven pollution control. Therefore, while economic structural changes facilitated long-term phosphorus reductions, policy enforcement provided the immediate regulatory pressure needed to achieve rapid declines post-2015. The interplay between these factors underscores the importance of integrating regulatory interventions with sustainable economic development to ensure continued environmental improvements.

Significant regional differences in phosphorus pollution levels exist within the YREB, reflecting an imbalance between economic development and pollution emissions. Over the past four decades, average phosphorus pollution levels in the upper reaches were 1.68 and 3.28 times higher than those in the middle and lower reaches, respectively. Fig. 2b illustrates the variation in NAPI across the three subregions relative to the entire region. The NAPI of western region was significantly lower than the regional average, with a declining trend over time. The NAPI of middle region mirrored the regional average, but a relative growth trend persisted over the past 20 years. From 2006 to 2015, the middle reaches' contribution to phosphorus pollution rose from 29.22 % to 33.54 %, driven by rapid population growth, industrial development, and urbanization in cities like Wuhan (Li et al., 2024a). The NAPI of eastern region was consistently higher than the regional average, with relative changes stabilizing after 2000. The downstream region accounted for the largest share of phosphorus pollution (45.73 %), highlighting its importance as a priority area for phosphorus management in the YREB. These findings indicate that environmental policies implemented in the YREB have had a differentiated impact across the upper, middle, and lower reaches. The downstream region's heightened human activity underscores the urgent need for targeted phosphorus management strategies to balance economic growth with environmental sustainability in the YREB.

3.2. Spatial distribution and trends of NAPI

The spatial distribution of NAPI demonstrates significant spatial clustering (Fig. S1). Global Moran's I values exceeding 0.35, z-scores above 11.5, and p-values below 0.001 from 1980 to 2020 (Table S4) confirm this pattern. Economically developed areas, such as Shanghai and Jiangsu, have emerged as NAPI hotspots, while economically less developed areas, such as Yunnan and Guizhou, are identified as NAPI cold spots (Fig. 3a). In 2020, 24 prefecture-level cities were classified as NAPI hotspots (99 % confidence), with an average NAPI of 647.18 kg/(km^2 a), whereas 13 cities were categorized as NAPI cold spots (99 % confidence), with an average NAPI of 131.03 kg/(km^2 a). The ratio between hotspots and cold spots is 4.94:1, reflecting substantial spatial imbalances in phosphorus input distribution. Ranking prefecture-level cities by phosphorus input in 2020 reveals that the top 10 % of cities

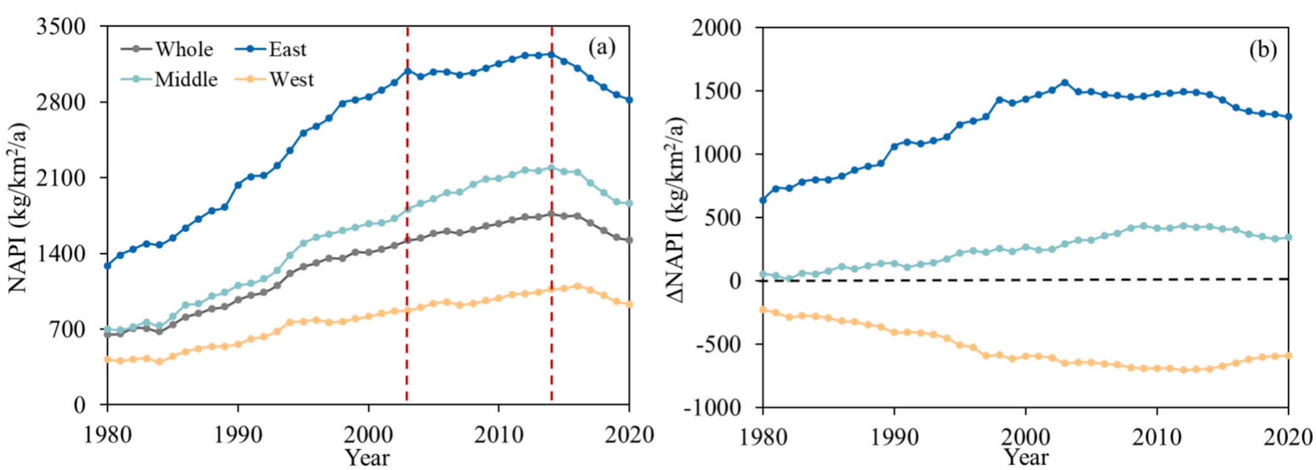

Fig. 2. NAPI of Yangtze River Economic Belt and three sub-regions (a) and the difference between the three sub-regions and whole from 1980 to 2020 (b).

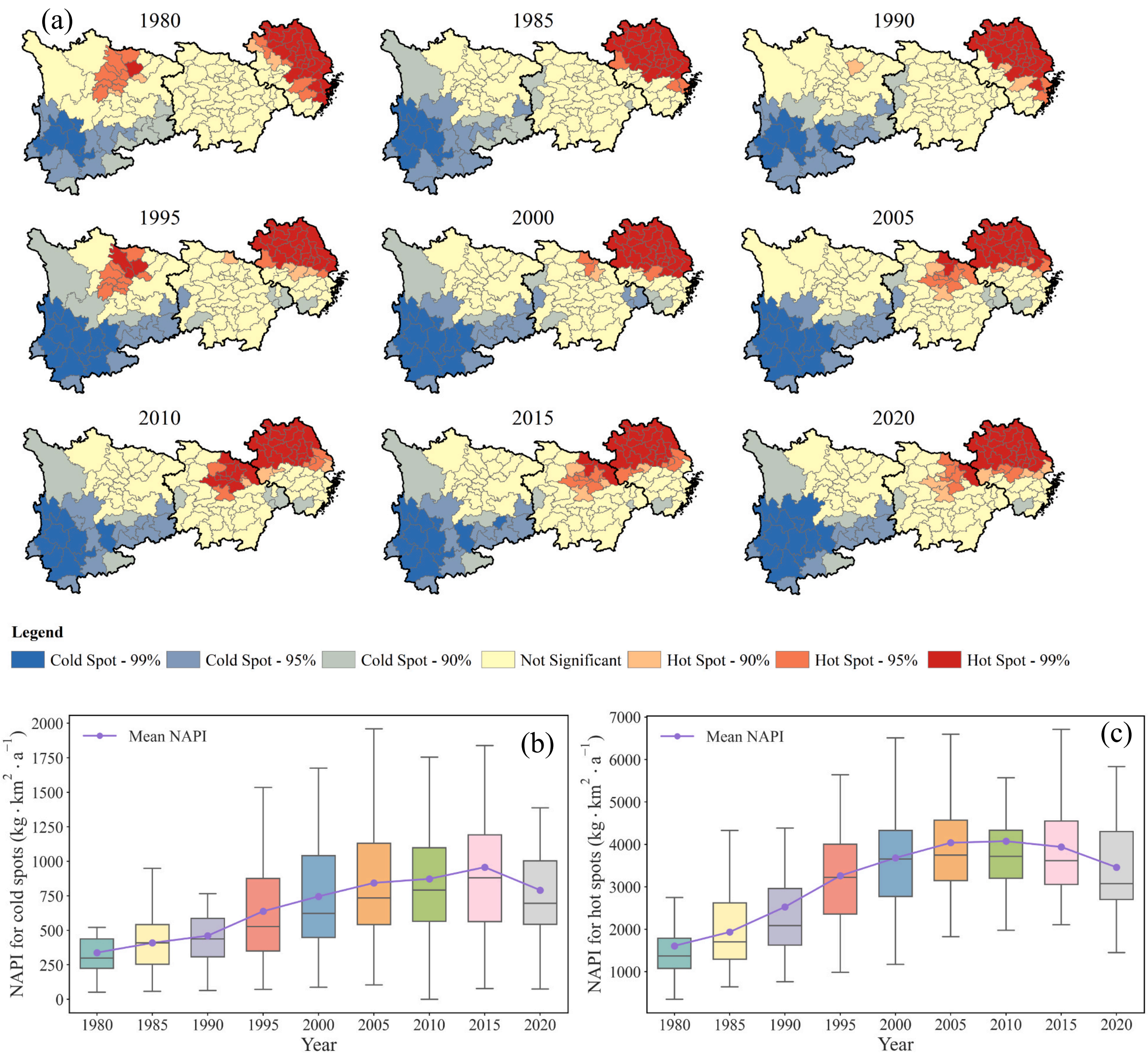

Fig. 3. Spatial distribution of cold-spots and hotspots from 1980 to 2020 (a) and data distribution of cold-spots (b) and hot spots (c).

accounted for 24.60 % of total inputs, while the bottom 10 % contributed only 2.01 %, resulting in a difference by a factor of 12.24. The temporal dynamics of hotspot and cold spot cities show that the number of hotspots increased from 26 in 1980 to a historical peak of 29 in 2010 before declining to 24 in 2020. Conversely, cold spots increased steadily from 6 in 1980 to 20 in 2020. These trends highlight the effectiveness of pollution control measures implemented in the Yangtze River Economic Belt over the past two decades, including industrial relocation and reductions in farmland fertilizer use. The data distribution of hotspots and cold spots between 1980 and 2020 exhibits an initial increase followed by a decline (Fig. 3b and c). Particularly during 1995–2005, the number of hotspots was 2 to 3 times greater than in other stages. This period marked a critical phase of China's economic development, characterized by rapid growth at the expense of environmental quality (Zhao et al., 2024). Notably, the peak average for hotspots (2005) occurred 10 years earlier than for cold spots (2015), underscoring regional differences in the timing and effectiveness of pollution control policies. China's adoption of a sustainable development strategy in 2000 (Xu et al., 2023; Yu et al., 2025), followed by measures in 2006 to reduce total pollutant emissions, played a pivotal role in gradually controlling pollution (Gao and Zheng, 2024). The introduction of the stringent "10-Point Water Plan" in 2015 marked a turning point, emphasizing comprehensive water quality monitoring and pollution management (Huang et al., 2019; Zhou et al., 2021). These policies have led to observable regional differences in phosphorus pollution control effectiveness. From a regional perspective, the share of phosphorus inputs from the eastern region declined from 51.47 % in 1980 to 44.59 % in 2020, while contributions from the middle region increased from 25.0 % to 32.61 %. The western region's share also rose, from a low of 21.95 % in 2005 to 23.10 % in 2020. These shifts indicate a gradual transfer of phosphorus inputs from the more developed eastern regions to the less developed middle regions, although the transfer to the western regions remains relatively slow (Jia et al., 2020). Despite this redistribution, the eastern region continues to be the primary source of phosphorus inputs and remains a key focus for pollution control efforts. Previous studies on phosphorus management in China and other developing regions have focused either on broad national trends (Wang et al., 2020) or case studies at the provincial level (Zhao et al., 2022). Our study advances the field by using high-resolution prefecture-level data spanning four decades, capturing localized pollution dynamics that national or provincial-level studies may overlook.

3.3. Effects of driving factors on phosphorus input

The application of chemical fertilizers to cropland (P_{fer}) is the primary driver of phosphorus input in the Yangtze River Economic Belt (Fig. 4), accounting for an average of 62.36 % over multiple years. Food/feed (P_{im}) and non-food (P_{nf}) phosphorus imports accounted for average proportions of 23.43 % and 14.21 %, respectively. From 1980 to 2020, P_{fer} exhibited an overall increasing trend across all regions, especially in the middle region, where it increased from 338.36 kg/(km^2 a) to 1120 kg/(km^2 a), representing a growth rate of 3.31 times. In comparison, the western and eastern regions experienced growth rates of 2.11 and 2.17 times, respectively. During 1980–2000, P_{im} and P_{nf} also exhibited an increasing trend, driven by population growth and rising demand for phosphorus-containing protein, as well as the expansion of livestock production, which increased phosphorus consumption in animal husbandry. To further analyze the phased evolution of NAPI driving factors, the study period (1980–2020) was divided into four stages (Fig. 4). From 1980 to 1990, P_{fer} made a significant contribution in the eastern region, exceeding 50 % of total phosphorus input. In contrast, P_{fer} contributions in the western region were below 50 %, indicating a higher reliance on food/feed and non-food phosphorus. With the rapid development of intensive agriculture and increased phosphorus production, P_{fer} became the dominant driver of phosphorus input across all regions from 1991 to 2000. The contribution of P_{fer} rose significantly, consistent with reference findings (Zhao et al., 2022), which indicated that P_{fer} accounted for nearly 60 % of total phosphorus input. As government investment in large-scale irrigation districts and upgrades to plain irrigation systems increased, agricultural activities intensified, particularly in the middle region from 2000 to 2010 (Li et al., 2024b; Xiang et al., 2022). Consequently, the contribution of P_{fer} in the middle region surpassed that of the eastern region. While chemical fertilizers remained the dominant driver in the middle and eastern regions, the western region experienced continued growth in P_{fer}, driven by the intensification of agricultural development from 2010 to 2020. By the end of the period, P_{fer} had become the primary driving factor for phosphorus input in the western region. The middle and eastern regions, characterized by high population density and intensive agricultural activity, serve as the grain production base of the YREB (Chen et al., 2024; Song et al., 2024), where chemical fertilizer phosphorus input plays a crucial role. In contrast, the western region historically relied on food/feed and non-food phosphorus inputs. However, with increasing agricultural development, P_{fer} has grown substantially in the western region, emerging as the dominant source of phosphorus input.

The effects of driving factors for phosphorus input within the Yangtze River Economic Belt were analyzed by LMDI model (Fig. 5a). Over the past 40 years, NAPI in the region increased by 1846 Gg, with distinct effects from different driving factors. Population growth, economic development, and industrial structure exerted positive influences, while phosphorus input intensity had a negative effect. Among the positive drivers, economic development contributed the most (77.8 %), followed by population growth (20.9 %). Economic growth has altered residents' dietary habits, with studies showing that protein intake proportion increases with rising incomes, thereby elevating phosphorus input (Gao et al., 2015; Huang et al., 2020). The negative effect of phosphorus input intensity highlights its suppressive role in reducing phosphorus input, as economic progress and industrial adjustments reduce pollution intensity, marking a turning point when GDP reaches a certain threshold (Kou et al., 2024; Zhang et al., 2020). Notably, urban and rural populations exhibited contrasting effects: urban populations promoted increased phosphorus input, while rural populations exerted a suppressive influence. This underscores the role of urbanization in driving higher phosphorus inputs (Zhang et al., 2024a; Zhang et al., 2024b). Additionally, while economic development positively impacted phosphorus input, the scale of primary industries showed a suppressive effect, reflecting a transition toward low-phosphorus, sustainable agricultural practices in the YREB (Yuan et al., 2023). Phosphorus input in

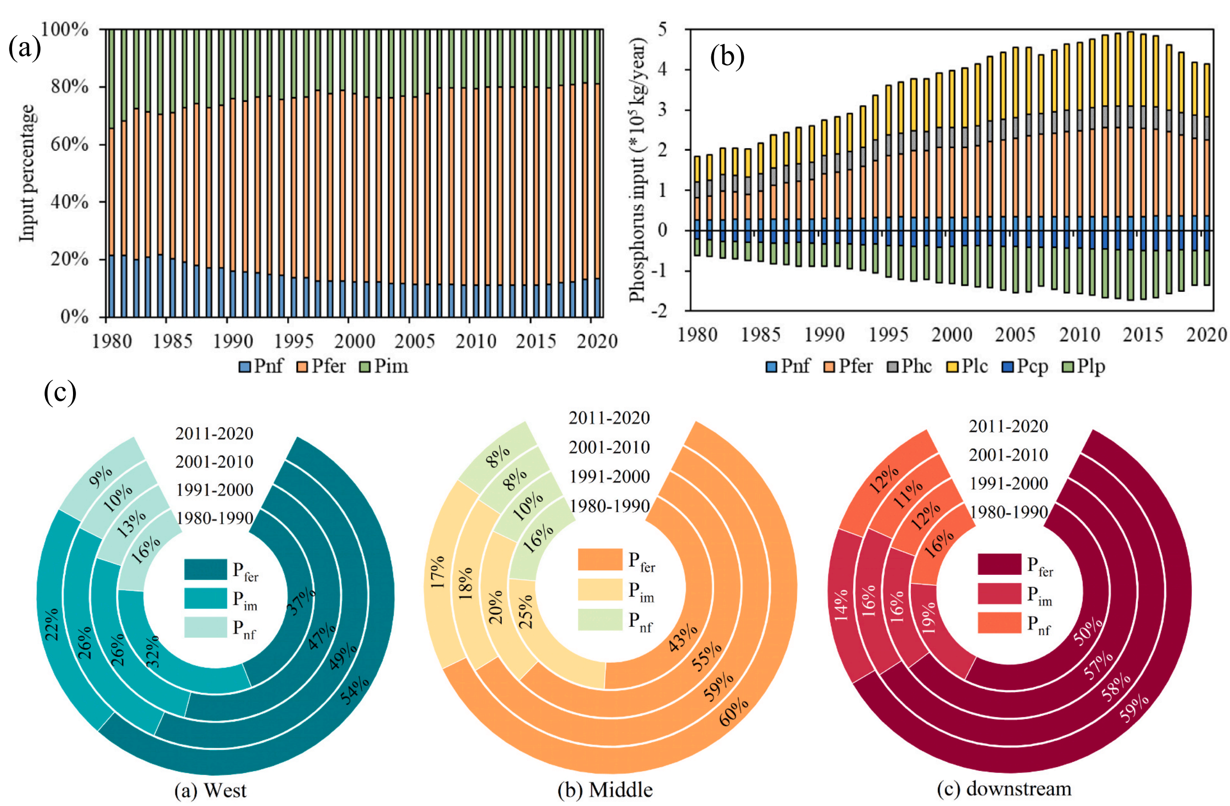

Fig. 4. Phosphorus input (b) and percentage (a) of the NAPI components for the whole region and for the sub-regions (c).

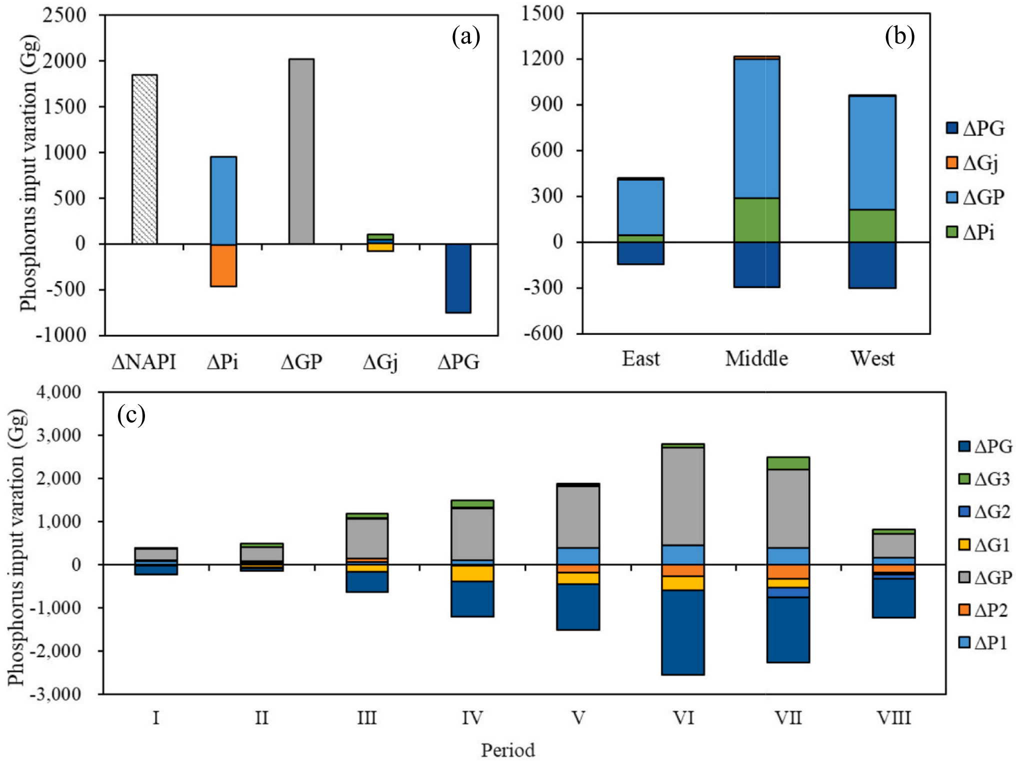

Fig. 5. Contribution variation of NAPI drivers' effects for the whole (a), sub-regions (b) and five years stage (c) (The legend of a is the same c).

the eastern, middle, and western regions increased by 8.6, 36.4, and 27.3 times, respectively, over the study period (Fig. 5b). The driving factors across regions mirrored those for the entire economic belt, with population, economic development, and industrial structure acting as positive drivers, and phosphorus input intensity serving as a suppressive factor. However, the contributions of these effects varied significantly: Eastern Region: Economic development was the dominant driver, accounting for 86.6 % of phosphorus input growth, compared to 75.1 % and 77.3 % in the middle and western regions, respectively. This suggests that per capita GDP is increasingly critical in driving regional phosphorus input (Peng et al., 2023). Population contributed only 10.8 %, indicating that in developed regions, population growth is no longer a key driver. Middle and Western Regions: Population growth contributed similarly to phosphorus input, at 23.5 % and 22.1 %, respectively, reflecting the ongoing influence of population dynamics in less developed areas. Analysis of five-year intervals revealed nonlinear trends in driving effects (Fig. 5c), particularly for economic development and phosphorus input intensity, which exhibited opposite patterns. The positive effect of economic development grew steadily from 1980 to 2010 before declining between 2010 and 2020, making it the primary driver of phosphorus input. In contrast, phosphorus input intensity showed a reverse trend, declining before 2010 and increasing thereafter, with 2010 marking a turning point. Analysis of five-year intervals revealed nonlinear trends in driving effects (Fig. 5c), particularly for economic development and phosphorus input intensity, which exhibited opposite patterns. The positive effect of economic development grew steadily from 1980 to 2010 before declining between 2010 and 2020, making it the primary driver of phosphorus input. In contrast, phosphorus input intensity showed a reverse trend, declining before 2010 and increasing thereafter, with 2010 marking a turning point. Overall, the economic development of the YREB has become a critical driver in reducing phosphorus input. Enhancing the quality of regional economic development, including the promotion of sustainable practices and advanced technologies, can further mitigate phosphorus input and support long-term environmental sustainability. Unlike previous research that treats phosphorus pollution as a uniform challenge (Li et al., 2020; Li et al., 2023a), our study emphasizes spatially targeted policy interventions based on economic and industrial characteristics of different regions. The study's integration of LMDI decomposition analysis allows for quantifying the role of economic development, industrial structure, and phosphorus input intensity in driving pollution trends—adding a methodological contribution to the field.

3.4. Nonlinear dynamics of NAPI and economic development

The relationship between NAPI and GDP per capita in the YREB exhibits a nonlinear, piecewise functional relationship characterized by two inflection points and three distinct stages (Fig. 6a). The first inflection point marks a change in the growth rate, occurring at a per capita GDP of 10,000 yuan and a NAPI of 1500 kg/(km^2 a). A significant difference in NAPI growth per unit GDP is observed before and after this point. During the first stage, NAPI demonstrates a power growth trend ($R^2 = 0.99$), increasing by 96.38 kg/(km^2 a) per 1000 yuan of per capita GDP-14.56 times higher than the growth rate in the second stage (6.62 kg/(km^2 a) per 1000 yuan). This inflection point, occurring in 2005, aligns with the initial stage of phosphorus input development in the economic belt (Fig. 2). At this time, China began prioritizing the coordinated development of economic growth and environmental protection. The second and third stages follow an inverted U-shaped trajectory ($R^2 = 0.93$), with the second inflection point representing the Environmental Kuznets Curve (EKC) turning point. This turning point corresponds to a per capita GDP of 45,000 yuan and a NAPI of 1700 kg/(km^2 a). Before the EKC turning point, NAPI increases by 6.62 kg/(km^2 a) per 1000 yuan of GDP, while after this point, it decreases by 9.00 kg/(km^2 a) per 1000 yuan. The EKC turning point, occurring in 2015, signifies a transition to a stage of coordinated development, where economic growth coincides with environmental improvement (Cai et al., 2020; Wang et al., 2023a). This phase coincided with China's implementation of its most stringent environmental management policies (Tang and Mao, 2024), leading to significant reductions in regional

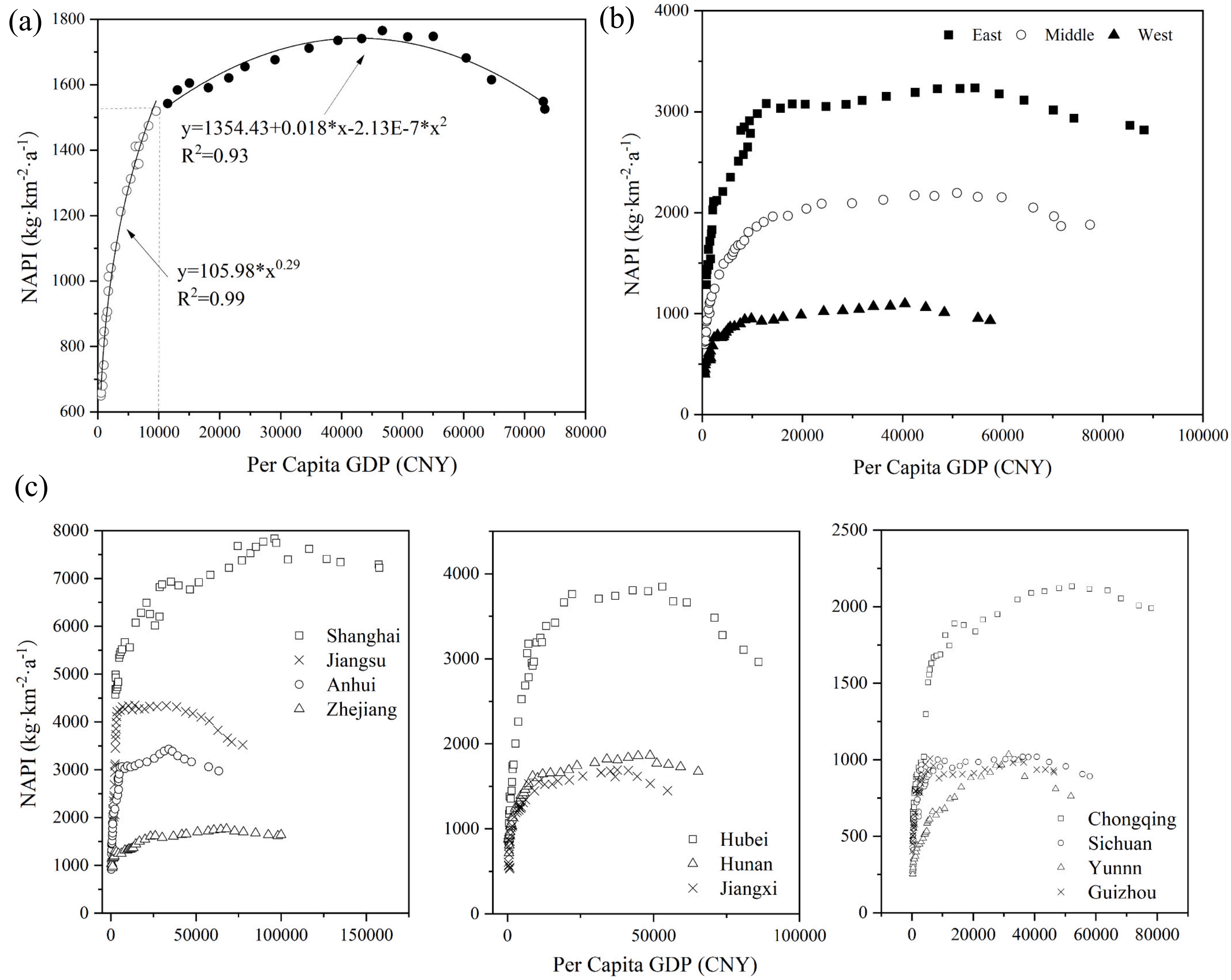

Fig. 6. Relationships between NAPI and GDP per capita of Yangtze River Economic Belt (a), sub-regions (b) and provinces (c).

phosphorus input. The relationship between per capita GDP and NAPI across the eastern, middle, and western regions of the YREB also exhibits an inverted U-shape (Fig. 6b). However, significant regional differences are evident in the timing of the EKC turning points, as well as the corresponding GDP and NAPI values: Eastern Region: The turning point occurred in 2013, earlier than the entire basin, with a corresponding NAPI of 3200 kg/(km^2 a) and a per capita GDP of 52,000 yuan. The per capita GDP-based NAPI at the turning point was 62.75 kg/(km^2·a·thousand RMB), 1.46 and 2.31 times that of the middle and western regions, respectively. Middle Region: The EKC turning point was reached in 2014, with a corresponding NAPI of 2200 kg/(km^2 a) and a per capita GDP of 50,000 yuan. Western Region: The turning point occurred in 2016, later than both the eastern and middle regions, with a NAPI of 1100 kg/(km^2 a) and a per capita GDP of 40,000 yuan. The "latecomer advantage" in the western region allows it to leverage the experiences of the eastern and middle regions in pollution management, reaching its phosphorus input turning point at a lower economic level (Mathews and Tan, 2011; Tang et al., 2022).

These regional disparities highlight the imbalance in economic and phosphorus input dynamics across the YREB. The relationship between per capita GDP and NAPI at the provincial level (Fig. 6c–e) reveals that, by 2020, most provinces had surpassed their EKC turning points, indicating significant progress in achieving coordinated development of economic growth and environmental pollution control within the YREB. Notably, Zhejiang Province, situated in the economically developed eastern region, did not exhibit disproportionately high NAPI values despite its advanced economic status. At its EKC turning point, Zhejiang's NAPI was comparable to that of Sichuan and Guizhou, the least developed provinces in the western region. This finding underscores the effectiveness of Zhejiang's sustainable development practices (Yang et al., 2024b), which have successfully decoupled economic growth from phosphorus input increases. Although the EKC turning point aligns with economic growth milestones, the reduction in phosphorus inputs was not an automatic consequence of rising GDP. Phosphorus input has decreased as a result of the combined effects of regulatory measures, technological advancements, and industrial structural adjustments, exhibiting distinct phased characteristics. Eastern Region: Transitioned earlier (2013) due to its advanced economy, stricter environmental policies, and better access to green technologies. Middle Region: Reached the EKC turning point around 2014, reflecting delayed but effective implementation of pollution control measures. Western Region: Lagged behind, achieving its turning point in 2016, leveraging the "latecomer advantage" by adopting best practices from the eastern and middle regions at a lower economic threshold. The western region has effectively used lessons from the eastern and middle regions to implement phosphorus reduction strategies at an earlier stage of its economic development. Unlike the eastern region, which faced high pollution levels before reaching the EKC turning point, the western region adopted pollution control strategies earlier, mitigating extreme pollution levels. This aligns with the theory that late-developing regions can "leapfrog" traditional pollution-intensive growth stages by adopting best practices from more developed regions (Iwami, 2005; Pegels and Altenburg, 2020). The economic structure of western region still resource- and agriculture-dependent, but targeted interventions, such as sustainable agricultural practices and stricter fertilizer regulations, have accelerated phosphorus reductions without requiring high levels of economic development. From a policy perspective, these findings offer actionable insights into phosphorus management across different economic contexts. Given the regional disparities in phosphorus input levels and economic development, one-size-fits-all regulatory approaches may be ineffective. Instead, we recommend region-specific phosphorus reduction targets, aligning with the distinct economic structures and pollution profiles of the eastern, middle, and western YREB subregions. For agricultural policies, promoting controlled-release fertilizers, precision farming, and integrated nutrient management can significantly reduce excess phosphorus application. Furthermore, the government could introduce subsidy programs to incentivize farmers to adopt environmentally friendly fertilization practices. In the industrial sector, stringent phosphorus recovery policies should be enforced, particularly in wastewater treatment plants and phosphorus-intensive manufacturing industries. Additionally, policies encouraging cleaner production processes through tax incentives and stricter emission limits can contribute to sustainable phosphorus management. These regionally tailored strategies will ensure that phosphorus pollution reduction is effectively integrated into broader economic and environmental planning efforts. The findings of this study have direct relevance to other developing countries experiencing rapid industrialization and agricultural expansion, such as India, Brazil, and Southeast Asian nations. Policymakers in these regions can learn from China's experience, particularly the importance of early intervention, regionalized pollution control strategies, and technology transfer to late-developing regions. The study highlights the need for economic-environmental coordination at multiple scales, ensuring that pollution mitigation efforts do not hinder economic growth but instead facilitate sustainable development.

3.5. Limitation and future research

Several limitations must be acknowledged. Although the NAPI framework has been previously applied in the Yangtze River Economic Belt, uncertainties remain due to the reliance on estimated phosphorus coefficients for fertilizer use, food consumption, and livestock production, which can vary across regions depending on agricultural practices and food waste levels. While GDP per capita serves as a useful proxy for economic development, it does not fully capture regional disparities in income distribution, informal economic activities, or differences in environmental policies, which could influence phosphorus pollution dynamics. This study contributes by identifying economic structure as the dominant factor driving phosphorus inputs, highlighting notable spatial heterogeneity in these drivers across provinces. Furthermore, external environmental factors such as climate change-through altered precipitation regimes, increased extreme weather events, and shifts in hydrological processes-may also impact phosphorus fluxes via runoff and soil erosion, underscoring the need for integrated socio-environmental analyses in future studies (Tilahun et al., 2024; Yang et al., 2024a). For instance, intensified storm events are likely to enhance surface runoff, thereby mobilizing and transporting higher phosphorus loads into aquatic systems, whereas prolonged droughts may reduce riverine dilution capacity, exacerbating phosphorus concentration and eutrophication risks (Carpenter et al., 2022; Mihiranga et al., 2021). Furthermore, rising temperatures may impact agricultural productivity and fertilizer application patterns, indirectly modifying phosphorus input dynamics. Future research should integrate climate variability and hydrological dynamics into NAPI assessments to provide a more comprehensive understanding of the coupled effects of anthropogenic and climatic influences on phosphorus fluxes. This could be achieved by coupling process-based hydrological models with NAPI estimation frameworks to simulate phosphorus transport under different climate scenarios. Additionally, given that climate-induced hydrological alterations may intensify regional disparities in phosphorus pollution, future studies should explore adaptive water resource management strategies that account for spatial heterogeneity in phosphorus fluxes. Such integrative approaches would enhance the predictive capability of phosphorus management policies and contribute to the development of climate-resilient nutrient governance frameworks. Incorporating digital technologies into phosphorus pollution management presents a promising avenue for improving real-time monitoring, data-driven policy interventions, and precision agriculture techniques. Emerging approaches such as remote sensing, geospatial big data analytics, artificial intelligence (AI)-assisted phosphorus modeling, and blockchain-based nutrient trading systems have the potential to revolutionize how phosphorus flows are tracked and managed (Yin et al., 2024; Yin and Zhao, 2024). Future research should explore how digital platforms can optimize phosphorus reduction strategies at different economic scales, enabling regional policymakers to dynamically adjust environmental regulations in response to real-time phosphorus flux data. Furthermore, smart farming technologies—such as IoT-based soil phosphorus sensors and AI-driven nutrient recommendation systems—could significantly improve phosphorus use efficiency in agriculture. Integrating these technologies with economic and environmental policies will be crucial for achieving sustainable phosphorus management in the Yangtze Economic Belt and beyond.

4. Conclusion

This study provides a comprehensive analysis of the relationship between NAPI and economic development in the YREB over the past four decades. By examining temporal trends, spatial distributions, and driving factors, the findings underscore the critical need for balancing economic growth with environmental sustainability. The insights gained contribute to the global discourse on managing phosphorus inputs in rapidly developing regions and offer actionable strategies for promoting sustainable development.

Key scientific contributions of this study include: (1) Identification of Dual EKC Turning Points: Unlike previous studies that assume a single EKC inflection point, this research reveals a two-stage turning point in phosphorus-economic dynamics, providing a more nuanced understanding of pollution trends in different economic contexts. (2) Revealing the Latecomer Advantage in Pollution Control: Less developed regions in the western YEB exhibit early phosphorus reductions at lower economic thresholds, benefiting from policy spillovers and technological diffusion from more developed regions. (3) Methodological Advancements: By combining NAPI modeling, LMDI decomposition, and EKC analysis, this study provides a comprehensive and quantitative assessment of phosphorus pollution drivers, distinguishing the roles of economic expansion, industrial structure, and policy interventions.

Beyond its scientific contributions, this study has significant policy implications for sustainable phosphorus management in rapidly developing regions: (1) Regionally Differentiated Policy Strategies: The observed regional disparities in phosphorus trends suggest that one-size-fits-all policies may be ineffective. Instead, targeted interventions are needed to address industrial phosphorus emissions in the east and agricultural phosphorus management in the west. (2) Enhancing Policy Spillover Effects: Given the latecomer advantage observed in less developed regions, policies promoting technology transfer, best practices in fertilizer application, and wastewater treatment expansion can accelerate phosphorus pollution reduction across the YEB. (3) Lessons for Other Developing Regions: The findings contribute to the broader discourse on phosphorus management, offering a replicable analytical framework for other rapidly developing economies facing similar pollution-development trade-offs, such as India, Brazil, and Southeast Asia.

In conclusion, this study advances the understanding of phosphorus-economic interactions at a finer spatial scale, uncovering new insights into regional disparities, turning points, and policy influences. These findings can inform more effective, region-specific phosphorus management strategies, ensuring that economic development is increasingly aligned with environmental sustainability in the Yangtze Economic Belt and beyond.

CRediT authorship contribution statement

Jincheng Li: Writing – original draft, Formal analysis, Data curation. **Xinyue Zhang:** Data curation. **Taher Kahil:** Writing – review & editing, Writing – original draft. **Dongni Chen:** Data curation. **Guangyao Wang:** Data curation. **Shasha Xu:** Data curation. **Yang Zhang:** Methodology. **Yan Chen:** Methodology.

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 research has been supported by the Young Scientists Fund of the National Natural Science Foundation of China (Grant No. 4240707 and 52409034), Beijing Natural Science Foundation (Grant No. 8244067), and China Postdoctoral Science Foundation (Grant No. 2023M740074, 2023M742426 and 2024T170022).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2025.113423.

Data availability

Data will be made available on request.

References

Ahmad, M., Jabeen, G., Wu, Y.Y., 2021. Heterogeneity of pollution haven/halo hypothesis and Environmental Kuznets Curve hypothesis across development levels of Chinese provinces. J. Clean. Prod. 285.
Alajmi, R.G., 2021. Factors that impact greenhouse gas emissions in Saudi Arabia: decomposition analysis using LMDI. Energ Policy.
Aminu, N., Clifton, N., Mahe, S., 2023. From pollution to prosperity: Investigating the Environmental Kuznets curve and pollution-haven hypothesis in sub-Saharan Africa's industrial sector. J. Environ. Manage. 342.
Bruhn, N.C.P., Viglioni, M.T.D., Nunes, R.F., Calegario, C.L.L., 2023. Recyclable waste in Brazilian municipalities: a spatial-temporal analysis before and after the national policy on solid waste. J. Clean. Prod. 421.
Cai, H., Mei, Y.D., Chen, J.H., Wu, Z.H., Lan, L., Zhu, D., 2020. An analysis of the relation between water pollution and economic growth in China by considering the contemporaneous correlation of water pollutants. J. Clean. Prod. 276.
Carpenter, S.R., Gahler, M.R., Kucharik, C.J., Stanley, E.H., 2022. Long-range dependence and extreme values of precipitation, phosphorus load, and Cyanobacteria. PNAS 119, e2214343119.
Chen, L., Xia, X.L., Zhang, J.Y., Zhu, Y.L., Long, C.Y., Chen, Y.J., Guo, W.L., Xu, L.Y., Jia, J., 2024. The food security risks in the Yangtze River Delta of China associated with water scarcity, grain production, and grain trade. Sci. Total Environ. 948.
Dalsgaard, J., Ekmann, K.S., Jensen, M.D., Pedersen, P.B., 2023. Reducing phosphorus emissions from net cage fish farming by diet manipulation. J. Environ. Manage. 334.
Deng, C.N., Liu, L.S., Peng, D.Z., Li, H.S., Zhao, Z.Y., Lyu, C.J., Zhang, Z.Q., 2021. Net anthropogenic nitrogen and phosphorus inputs in the Yangtze River economic belt: spatiotemporal dynamics, attribution analysis, and diversity management. J. Hydrol. 597.
Diamond, M.L., Wang, Z.Y., 2024. Safe and just earth system boundaries for novel entities. Environ Sci Tech Let 11, 770–772.
Durmaz, N., Thompson, A., 2024. An environmental Kuznets curve for water pollution: does water abundance affect the turning point? Sci. Total Environ. 913, 169657. https://doi.org/10.1016/j.scitotenv.2023.169657.
Farooq, U., Bhanja, N., Rather, S.R., Dar, A.B., 2024. From pollution to prosperity: Using inverted N-shaped environmental Kuznets curve to predict India's environmental improvement milestones. J. Clean. Prod. 434.
Fu, J.X., Li, J.C., Cai, K.K., Liu, Y., 2024. Net anthropogenic nitrogen and phosphorus input and its spatial heterogeneity at urban scale in China. Sci. Geogr. Sin. 44, 513–522 in Chinese.
Gao, W., Duan, Z.Z., Yan, C.A., Liu, C.G., 2020. Influence of nutrient mitigation measures on the fractional export of watershed inputs in an urban watershed. Environ. Sci. Pollut. R. 27, 18521–18529.
Gao, W., Howarth, R.W., Swaney, D.P., Hong, B.G., Guo, H.C., 2015. Enhanced N input to Lake Dianchi Basin from 1980 to 2010: Drivers and consequences. Sci. Total Environ. 505, 376–384.
Gao, Y.Y., Zheng, J.H., 2024. The opposite innovation impacts of air and water pollution regulations: evidence from the total emissions control policy in China. J. Asian Econ. 92.
Guan, D.J., Chen, S., Zhang, Y.X., Liu, Z.F., Peng, G.C., Zhou, L.L., 2024. Influencing factors and the establishment of a basin ecological compensation mechanism from the perspective of water conservation: a case study of the upper Yangtze River in China. J. Clean. Prod. 456.
Guan, Q., Feng, L., Hou, X.J., Schurgers, G., Zheng, Y., Tang, J., 2020. Eutrophication changes in fifty large lakes on the Yangtze Plain of China derived from MERIS and OLCI observations. Remote Sens. Environ. 246.
Guo, X., Shahbaz, M., 2024. The existence of environmental Kuznets curve: Critical look and future implications for environmental management. J. Environ. Manage. 351.
Houssini, K., Geng, Y., Liu, J.Y., Zeng, X.L., Hohl, S.V., 2023. Measuring anthropogenic phosphorus cycles to promote resource recovery and circularity in Morocco. Resour. Policy 81, 103415. https://doi.org/10.1016/j.resourpol.2023.103415.
Huang, J.C., Zhang, Y.J., Arhonditsis, G.B., Gao, J.F., Chen, Q.W., Wu, N.C., Dong, F.F., Shi, W.Q., 2019. How successful are the restoration efforts of China's lakes and reservoirs? Environ. Int. 123, 96–103.
Huang, S., Xia, J., Wang, Y.L., Wang, G.S., She, D.X., Lei, J.R., 2024. Pollution loads in the middle-lower Yangtze River by coupling water quality models with machine learning. Water Res. 263, 122191. https://doi.org/10.1016/j.watres.2024.122191.
Huang, W., Gao, B., Lin, J.Y., Cui, S.H., Zhong, Q.M., Huang, C.L., 2020. Driving forces of nitrogen input into city-level food systems: comparing a food-source with a food-sink prefecture-level city in China. Resour Conserv Recy 160, 104850. https://doi.org/10.1016/j.resconrec.2020.104850.
Iwami, T., 2005. The "advantage of latecomer" in abating air-pollution: the East Asian experience. Int. J. Soc. Econ. 32, 184.
Jaganathan, S., Rajiva, A., Amini, H., Bont, J., Dixit, S., Dutta, A., Kloog, I., Lane, K.J., Menon, J.S., Nori-Sarma, A., Prabhakaran, D., Schwartz, J., Sharma, P., Stafoggia, M., Walia, G.K., Wellenius, G.A., Prabhakaran, P., Ljungman, P., Mandal, S., 2025. Nationwide analysis of air pollution hotspots across India: a spatiotemporal PM2.5 trend analysis (2008-2019). Environ. Res. 264 (Pt 1), 120276. https://doi.org/10.1016/j.envres.2024.120276.
Ji, L., Sun, Y.A., Liu, J.W., Chiu, Y.H., 2023. Analysis of the circular economy efficiency of China's industrial wastewater and solid waste- based on a comparison before and after the 13th Five-Year Plan. Sci. Total Environ. 881.
Jia, J.X., Ma, G.R., Qin, C., Wang, L.Y., 2020. Place-based policies, state-led industrialisation, and regional development: evidence from China's Great Western Development Programme. Eur. Econ. Rev. 123, 103398. https://doi.org/10.1016/j.euroecorev.2020.103398.
Ju, C., Zhou, C., Zhang, L., 2025. Characteristics of phosphorus fertilizer application in the Yangtze River Economic Belt. China. Earth Critical Zone 2, 100027.
Kou, J.W., Ma, W.J., Wang, X.Y., Li, C.Y., Liang, T.T., 2024. Income-based environmental effects of family food consumption and the affordability towards healthy diets. Sustain Prod Consump 51, 371–384.
Li, B., Li, P., Zeng, X.C., Yu, W., Huang, Y.F., Wang, G.Q., Young, B.R., 2020. Assessing the sustainability of phosphorus use in China flow patterns from 1980 to 2015. Sci. Total Environ. 704.
Li, H.F., Han, Y.J., Wang, T., Wang, Z.H., Li, Y.A., Shen, H.F., 2024a. Evolution of urban morphological polycentricity and the thermal response in Wuhan from 2000 to 2020. Sustain. Cities Soc. 100, 105055. https://doi.org/10.1016/j.scs.2023.105055.
Li, J.C., Chen, Y., Cai, K.K., Fu, J.X., Ting, T., Chen, Y.H., Folberth, C., Liu, Y., 2022. A high-resolution nutrient emission inventory for hotspot identification in the Yangtze River Basin. J. Environ. Manage. 321.
Li, J.C., Hu, M.C., Ma, W.J., Liu, Y., Dong, F.F., Zou, R., Chen, Y.H., 2023a. Optimization and multi-uncertainty analysis of best management practices at the watershed scale: a reliability-level based bayesian network approach. J. Environ. Manage. 331.
Li, J.C., Jiang, Q.S., Cai, K.K., Fu, J.X., Liu, Y., Chen, D.N., Liu, X.Y., Dai, H.C., Chen, Y.H., Chen, Y., 2023b. Uncovering the spatially uneven synergistic effects of China?s enterprise-level industrial water pollutants reduction. Resour. Conserv. Recy. 190.
Li, X.J., Yang, Y.H., Zhou, X.Y., Liu, L.L., Yang, Y.M., Han, S.M., Zhang, Y.S., 2024b. Impact of water productivity and irrigated area expansion on irrigation water consumption and food production in China in last four decades. Agr. Water Manage. 304, 109100. https://doi.org/10.1016/j.agwat.2024.109100.
Liao, J.Q., Zhang, N., 2024. Environmental regulation and manufacturing employment: evidence from China's Eleventh Five-Year Plan. China. Econ. Rev. 87.
Lin, B.Q., Omoju, O.E., Nwakeze, N.M., Okonkwo, J.U., Megbowon, E.T., 2016. Is the environmental Kuznets curve hypothesis a sound basis for environmental policy in Africa? J. Clean. Prod. 133, 712–724.

Lin, W.F., Lin, K., Du, L.Z., Du, J.H., 2023. Can regional joint prevention and control of atmospheric reduce border pollution? Evidence from China's 12th Five-Year Plan on air pollution. J. Environ. Manage. 342.

Liu, D.D., Bai, L., Li, X.Y., Zhang, Y., Qiao, Q., Lu, Z.B., Liu, J.Y., 2022. Spatial characteristics and driving forces of anthropogenic phosphorus emissions in the Yangtze River Economic Belt, China. Resour Conserv Recy 176, 105937. https://doi.org/10.1016/j.resconrec.2021.105937.

Liu, Y.B., Song, C.L., Yang, X., Zhuo, H.H., Zhou, Z., Cao, L., Cao, X.Y., Zhou, Y.Y., Xu, J., Wan, L.L., 2024. Hydrological regimes and water quality variations in the Yangtze River basin from 1998 to 2018. Water Res. 249, 120910. https://doi.org/10.1016/j.watres.2023.120910.

Mathews, J.A., Tan, H., 2011. Progress toward a circular economy in China the drivers (and inhibitors) of eco-industrial initiative. J. Ind. Ecol. 15, 435–457.

Mihiranga, H.K.M., Jiang, Y., Li, X., Wang, W., De Silva, K., Kumwimba, M.N., Bao, X., Nissanka, S.P., 2021. Nitrogen/phosphorus behavior traits and implications during storm events in a semi-arid mountainous watershed. Sci. Total Environ. 791, 148382.

Pegels, A., Altenburg, T., 2020. Latecomer development in a "greening" world: introduction to the Special Issue. World Dev. 135.

Peng, L., Deng, X.Z., Li, Z.H., 2023. An extended input-output analysis of links between industrial production and water pollutant discharge in the Yangtze River Economic Belt. J. Clean. Prod. 390.

Qin, C.B., Su, J.Q., Xiao, Y., Qiang, Y., Xiong, S.A., 2023. Assessing the Beautiful China initiative from an environmental perspective: indicators, goals, and provincial performance. Environ. Sci. Pollut. R. 30, 84412–84424.

Qin, C.B., Xue, Q., Zhang, J.W., Lu, L., Xiong, S.G., Xiao, Y., Zhang, X.J., Wang, J.N., 2024. A beautiful China initiative towards the harmony between humanity and the nature. Front. Env. Sci. Eng 18.

Russell, M.J., Weller, D.E., Jordan, T.E., Sigwart, K.J., Sullivan, K.J., 2008. Net anthropogenic phosphorus inputs: spatial and temporal variability in the Chesapeake Bay region. Biogeochemistry 88, 285–304.

Shen, W.Z., Li, S.S., Zhuang, Y.H., He, J., Liu, H.B., Zhang, L., 2023. Phosphorus use efficiency has crossed the turning point of the environmental Kuznets curve: opportunities and challenges for crop production in China. J. Environ. Manage. 326.

Song, J.R., Hu, S.G., Frazier, A.E., Wu, S., Wang, M., 2024. Will industrial structure changes promote or reduce non-grain production? Evidence from the Yangtze River economic belt. J. Clean Prod. 466.

Tang, W.Z., Pei, Y.S., Zheng, H., Zhao, Y., Shu, L.M., Zhang, H., 2022. Twenty years of China's water pollution control: experiences and challenges. Chemosphere 295.

Tang, Y., Mao, Y.J., 2024. Centralization and border water pollution: evidence from China's environmental enforcement reform. J. Clean. Prod. 481.

Tilahun, A.B., Dürr, H.H., Schweden, K., Flörke, M., 2024. Perspectives on total phosphorus response in rivers: examining the influence of rainfall extremes and post-dry rainfall. Sci. Total Environ. 940.

Van Staden, T.L., Meter, K.J., Basu, N.B., Parsons, C.T., Akbarzadeh, Z., Cappellen, P., 2022. Agricultural phosphorus surplus trajectories for Ontario, Canada (1961–2016), and erosional export risk. Sci. Total Environ. 818, 151717. https://doi.org/10.1016/j.scitotenv.2021.151717.

Wang, H., Liu, C., Xiong, L.C., Wang, F.T., 2023a. The spatial spillover effect and impact paths of agricultural industry agglomeration on agricultural non-point source pollution: a case study in Yangtze River Delta, China. J. Clean Prod. 401.

Wang, H.H., He, W.L., Zhang, Z.Y., Liu, X.H., Yang, Y.S., Xue, H.Y., Xu, T.T., Liu, K.L., Xian, Y.J., Liu, S.R., Zhong, Y.H., Gao, X.Y., 2024. Spatio-temporal evolution mechanism and dynamic simulation of nitrogen and phosphorus pollution of the Yangtze River economic belt in China. Environ. Pollut. 357, 124402. https://doi.org/10.1016/j.envpol.2024.124402.

Wang, J.D., Dong, K.Y., Hochman, G., Timilsina, G.R., 2023b. Factors driving aggregate service sector energy intensities in Asia and Eastern Europe: a LMDI analysis. Energy Policy 172.

Wang, M., Feng, C., 2021. The win-win ability of environmental protection and economic development during China's transition. Technol. Forecast. Soc. 166.

Wang, T.X., Sun, Y., Wang, T.Z., Wang, Z.X., Hu, S.D., Gao, S.J., 2023c. Dynamic spatiotemporal change of net anthropogenic phosphorus inputs and its response of water quality in the Liao river basin. Chemosphere 331.

Wang, W., Yang, G., 2025. Sustainable carrying capacity: Integrating SDGs to assess evidence of sustainable development: a case study of the Yangtze River Economic Belt in China. J. Clean. Prod. 486, 144569.

Wang, Y.S., Xie, X., Liu, C., Wang, Y.Y., Li, M., 2020. Variation of net anthropogenic phosphorus inputs (NAPI) and riverine phosphorus fluxes in seven major river basins in China. Sci. Total Environ. 742, 140514. https://doi.org/10.1016/j.scitotenv.2020.140514.

Wu, Z., Li, J.C., Sun, Y.X., Peñuelas, J., Huang, J.L., Sardans, J., Jiang, Q.S., Finlay, J.C., Britten, G.L., Follows, M.J., Gao, W., Qin, B.Q., Ni, J.R., Huo, S.L., Liu, Y., 2022. Imbalance of global nutrient cycles exacerbated by the greater retention of phosphorus over nitrogen in lakes. Nat. Geosci. 15, 464–468.

Xiang, W.L., Tan, M.B., Yang, X., Li, X.B., 2022. The impact of cropland spatial shift on irrigation water use in China. Environ. Impact Asses 97, 106904. https://doi.org/10.1016/j.eiar.2022.106904.

Xu, H., Deng, H., Zhang, D.W., 2023. Fine-grained sustainability assessment: county sustainable development in China from 2000 to 2017. J. Clean. Prod. 425, 138798. https://doi.org/10.1016/j.jclepro.2023.138798.

Yang, C.L., Hu, Y.X., Li, Z.W., Yu, X.X., 2024a. Relating rainfall, runoff, and sediment to phosphorus loss in northern rocky mountainous area of China. Catena 247.

Yang, J.L., Li, M., Liu, L., Zhao, H.J., Luo, W.Q., Guo, Y.L., Ji, X.A., Hu, W., 2023. Dynamic characteristics of net anthropogenic phosphorus input to the upper Yangtze River Basin from 1989 to 2019: focus on the phosphate ore rich area in China. J. Environ. Manage. 347.

Yang, X., He, G., Zhu, Z.H., Zhao, S.H., Zhang, S.Y., 2024b. Evolutionary game analysis and efficiency test of water pollution control driven by emission trading: evidence from Zhejiang Province, China. Heliyon 10.

Yang, X., Ran, G.G., 2024. Factors influencing the coupled and coordinated development of cities in the Yangtze River Economic Belt: a focus on carbon reduction, pollution control, greening, and growth. J. Environ. Manage. 370.

Yin, S., Wang, Y.R., Liu, Y.J., Wang, S., 2024. Exploring drivers of behavioral willingness to use clean energy to reduce environmental emissions in rural China: an extension of the UTAUT2 model. J. Renew. Sustain. Energy 16.

Yin, S., Zhao, Y.D., 2024. Digital green value co-creation behavior, digital green network embedding and digital green innovation performance: moderating effects of digital green network fragmentation. Hum. Soc. Sci. Commun. 11.

Yu, C.Y., Shen, W.C., Zhang, Z.F., 2025. Assessing progress toward sustainable development in China and its impact on human well-being. Environ. Impact Asses 110.

Yuan, L., Li, R.Y., Wu, X., He, W.J., Kong, Y., Ramsey, T.S., Degefu, D.M., 2023. Decoupling of economic growth and resources-environmental pressure in the Yangtze River economic belt, China. Ecol. Indic. 153.

Zhang, P., Wang, Y.Y., Chen, M., Cai, Y.P., Su, S.L., Tan, Q., Xie, Y.L., 2024a. Unveiling the complexities of sustainable urban phosphorus management based on lifecycle assessment and decomposition analysis. Sustain Futures 7.

Zhang, X.L., Zhang, Y., Fath, B.D., 2020. Analysis of anthropogenic nitrogen and its influencing factors in Beijing. J. Clean. Prod. 244.

Zhang, Y.Y., Sun, M.Y., Yang, R.J., Li, X.H., Zhang, L., Li, M.Y., 2021. Decoupling water environment pressures from economic growth in the Yangtze River Economic Belt, China. Ecol. Indic. 122.

Zhang, Z.Q., Sun, L.H., Deng, C.N., Dong, L., Xu, R., Nie, C., Yang, Q.P., 2024b. A new perspective on anthropogenic nitrogen loss mitigation strategies: integrated control via sustainable regional integration. Sci. Total Environ. 916.

Zhao, J.H., Chen, W., Liu, Z.X., Liu, W., Li, K.Y., Zhang, B., Zhang, Y.G., Yu, L., Sakai, T., 2024. Urban expansion, economic development, and carbon emissions: trends, patterns, and decoupling in mainland China's provincial capitals (1985-2020). Ecol. Ind. 169.

Zhao, Z.Y., Zhang, L.X., Deng, C.N., 2022. Changes in net anthropogenic nitrogen and phosphorus inputs in the Yangtze River Economic Belt, China (1999–2018). Ecol. Ind. 145, 109674. https://doi.org/10.1016/j.ecolind.2022.109674.

Zheng, J., Yuan, B.B., Wu, J.L., Chen, S.W., 2024. The impact of manufacturing agglomeration on green development performance: evidence from the Yangtze river economic belt in China. J. Clean. Prod. 471.

Zhong, W.J., Wang, S.R., Dong, Y., Ni, Z.K., Fan, Y., Wu, D.S., 2022. Trends of the response-relationship between net anthropogenic nitrogen and phosphorus inputs (NANI/NAPI) and TN/TP export fluxes in Raohe basin, China. Chemosphere 286.

Zhou, Z.F., Liu, J.H., Zhou, N.X., Zhang, T., Zeng, H.X., 2021. Does the "10-Point Water Plan" reduce the intensity of industrial water pollution? Quasi-experimental evidence from China. J. Environ. Manage 295.

Zhu, D.L., Dai, Y.T., Zhang, H., Cheng, J., Jiang, X., Ji, X.X., 2022. Whether ecological measures have influenced the environmental Kuznets curve (EKC)? An analysis using land footprint in the Weihe River Basin, China. Ecol. Indic. 139.