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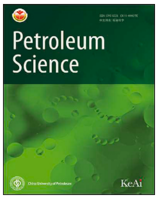

Original Paper

Has the Belt and Road Initiative reshaped the ecological sustainability of Eurasia: A perspective of three-dimensional ecological footprint

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ABSTRACT

At present, environmental problems are becoming increasingly severe, and sustainable development concerns the common destiny of all mankind around the world. Leveraging ecological footprint and ecological carrying capacity data for Eurasia from 2000 to 2022, this study employs a three-dimensional ecological footprint model to conduct a multi-scale sustainability assessment. Further applying a difference-in-differences model, we analyze the impact mechanisms of the Belt and Road Initiative on Eurasia's ecological footprint. Quantile regression and heterogeneity analysis reveal Belt and Road Initiative's differential effects across countries. Key findings indicate that: (1) Eurasia's unsustainable development intensified from 2000 to 2022, with ecological footprint depth rising from 1.966 to 2.513 ha/cap, while per capita ecological footprint size declined slightly from 1.092 to 1.023 ha/cap. (2) Classifying 83 countries into 9 sustainability types based on ecological footprint depth and size, Asia showed weak sustainability (low size-medium depth and low size-low depth types), while Europe was primarily low size-medium depth with relatively stronger sustainability. Six countries experienced weakened sustainability and six improved. (3) The Belt and Road Initiative significantly increased ecological footprint in Eurasian countries, mediated by industrial structure, technological innovation, and foreign direct investment. Quantile regression indicates Belt and Road Initiative's effect is stronger in nations with lower initial ecological footprint. Heterogeneity analysis further shows Belt and Road Initiative disproportionately impacts countries with lower ecological footprint depth, smaller per capita ecological footprint size, and weaker sustainability. These insights provide critical guidance for implementing the UN 2030 Agenda and formulating Belt and Road Initiative policies to enhance long-term sustainability.

1. Introduction

Sustainable development is a grand cause that concerns the common destiny of people worldwide and has garnered global attention (Jia et al., 2024). This concept stems from humanity's extensive concern about increasingly severe environmental issues and profound reflection on the industrial revolution process (Basheer et al., 2022). In recent years, significant achievements have been made worldwide in eradicating hunger and poverty and improving the quality of the living environment. According to the "World Population Prospects 2024" released by the United Nations, as of July 2024, the global population had reached nearly 8.2 billion and was projected to increase by 2 billion over the next 60 years. From 2000 to 2023, China's total energy consumption rose from 1.47 billion tons of standard coal to 5.72 billion tons of standard coal, with an average annual growth rate of 12%. Meanwhile, global energy demand has been growing at an annual rate of 2.8% (Abbasi et al., 2022). The rapid growth in population and energy consumption has become a source of pressure, posing severe threats to natural capital (Dong et al., 2021). However, as a common global approach to addressing challenges, sustainable development serves as a core concept driving the pace of global progress. In 2015, the United Nations Sustainable Development Summit adopted the "2030 Agenda for Sustainable Development",

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outlining 17 sustainable development goals (Colglazier, 2015), marking a new phase in sustainable development.

Sustainable development is a key topic at the intersection of theoretical science and applied practice in the new era (Wang et al., 2024a). As the demand for natural resources and ecosystem services continues to grow, managing ecological assets to ensure sustainable development has become a focal point for policymakers. Therefore, there is an urgent need for an approach to monitor the impact of human activities on regional resource and environmental performance (Wang et al., 2024c). Early research used pollutants as ecological indicators, such as carbon dioxide emissions (Zhang et al., 2024). However, from a sustainable development perspective, these pollutants do not provide a comprehensive assessment of ecological vulnerability and measurement of sustainability (Nketiah et al., 2024), necessitating a more precise and comprehensive indicator to fully reflect the integrated state of sustainable development. Literature on environmental sustainability emphasizes the importance of using the ecological footprint (EF) as a more accurate indicator than traditional pollutants to assess the degree of environmental harm. The EF converts different types of natural capital into biologically productive land, providing an intuitive reflection of human occupation of natural capital (Sun and Wang, 2022). The traditional EF analysis method fails to distinguish between flow capital and stock capital, which is a core issue in sustainable development (Fang, 2013), while it can comprehensively and intuitively assess the utilization of regional natural capital (Long et al., 2020). To address this issue, Niccolucci et al. (2009) proposed a three-dimensional ecological footprint model incorporating ecological footprint depth (EFD) and ecological footprint size (EFS) to represent the extent of stock capital occupation and flow capital consumption. In this study, we choose the three-dimensional ecological footprint model to assess regional sustainable development status.

In 2013, China launched the “Belt and Road” Initiative (BRI), aiming to achieve long-term socio-economic development through global economic integration, stimulating economic and infrastructure development, as well as financial integration (Thacker et al., 2019). As of today, the BRI has covered 156 countries across Africa, Asia, Europe, North America, South America, and Oceania, with their combined GDP accounting for 24.78% of the global total and their population representing 50.13% of the world's total. The BRI involves extensive globalization, international cooperation, and large-scale projects, providing substantial financial and technical resources to partner countries (Hughes et al., 2020). Investment serves as a crucial driver of economic growth, particularly in the BRI region, where 86% of the countries are developing countries (Yang et al., 2025). As of the end of 2023, China's investment stock in the BRI region amounted to USD 171.37 billion. Investments in capital assets such as infrastructure and power plants are vital for socio-economic development in this context. These investments not only drive infrastructure construction, improve transportation and logistics efficiency, and promote industrialization but also create numerous jobs (Wang et al., 2024). However, in the long run, these projects may pose challenges to sustainable development (Saud et al., 2020). Early studies have provided tangible evidence of a range of negative impacts related to economic growth, biodiversity, climate stability, resource security, and environmental sustainability (Hunjra et al., 2014; Laurance and Arrea, 2017; Lu et al., 2020; Tracy et al., 2017). Furthermore, these impacts vary among BRI countries at different stages of development (Hinsley et al., 2020). Therefore, while promoting the BRI, it is essential to pay attention to the potential environmental issues it may bring. In response to this issue, the China Council for International Cooperation on Environment and Development held a forum themed “Green BRI and the 2030 Agenda for Sustainable Development” in September 2021, emphasizing green BRI construction will bring new opportunities for achieving the sustainable development goals, balancing socio-economic objectives with the promotion of environmental quality improvement. At the 2025 “Belt and Road” International Cooperation Forum, China emphasized the need to promote the green and low-carbon development of infrastructure, advocate green, low-carbon, circular and sustainable production and lifestyle, strengthen cooperation in ecological and environmental protection, build an ecological civilization, and jointly achieve the 2030 Sustainable Development Goals. This is a call to monitor progress towards achieving social, economic, and environmental sustainability goals across the entire BRI region.

The BRI has profoundly promoted global sustainable development through economic, environmental and social dimensions: Economically, it has increased trade volume between China and the five Central Asian countries from 312.04 billion yuan in 2013 to 674.15 billion yuan in 2024; environmentally, it has comprehensively halted new coal-fired power projects abroad, promoted green infrastructure standards, and exported pollution control technologies, such as the introduction of a super monitoring station from the Chinese Academy of Environmental Sciences to Bangkok, Thailand, to address complex pollution, and the construction of a water intake dam at the Kamchay Hydropower Station in Cambodia to prevent seawater intrusion, benefiting 600,000 residents' water supply; socially, the China-Pakistan Economic Corridor has created 230,000 jobs, and the construction phase of the Jakarta-Bandung High-Speed Railway in Indonesia has provided 51,000 job opportunities.

The selection of Eurasia as the study sample in this paper is well-considered. Firstly, as the center of the world political stage, Eurasia is a crucial region for the construction of the BRI, a core area for global economic and trade cooperation, a hotspot for geopolitical conflicts, and a region of intense response to global climate change (Brzezinski, 2016). Secondly, this region is rich in underground and surface resources, attracting investments and cooperation opportunities from various countries and enterprises (İlarslan and Bayat, 2024). For instance, data from the World Bank indicated that Eurasia held the largest reserves of fossil fuels and mineral resources. Thirdly, various regions of Eurasia are located in sensitive areas for climatic and geological changes, with complex and diverse ecosystems interact with each other, making it one of the most vulnerable regions globally in terms of the ecological environment (Qin et al., 2022). Consequently, the environmental, economic, and social risks posed by climate change, primarily caused by carbon emissions, are increasingly significant. In this regard, all Eurasian countries have become members of the Paris Agreement, which was signed in 2015 and entered into force in 2016. Focusing on the sustainable development of the ecological environment and socio-economy of Eurasia not only benefits the prosperity and development of Eurasian countries but also provides a solid foundation for international cooperation. Therefore, the aforementioned reasons constitute the primary motivations for our focus on Eurasia.

This paper makes marginal contributions primarily in the following aspects. Firstly, it takes Eurasia as the study object and systematically analyzes the level of sustainable development in this region from 2000 to 2022 across multiple scales, including the plate, continent, and country dimensions. Secondly, based on an in-depth analysis of EFD and EFS, it uses the natural breaks classification method to classify 83 countries into 9 types of sustainable development, providing a strong basis for formulating differentiated development strategies. Lastly, the paper empirically analyzes the impact of the BRI on the EF of Eurasian countries and its mechanism using a difference-in-differences (DID) model.

Additionally, it combines quantile regression and heterogeneity analysis to demonstrate the differential impact of the BRI on the EF of different countries from multiple dimensions. The research findings can provide important guidance for implementing the "2030 Agenda for Sustainable Development" and formulating related policies, thereby enhancing the long-term sustainability of the BRI.

This paper is organized as follows: Section 1 introduces the research background. Section 2 reviews the relevant literature. Section 3 introduces materials and methods. The results and discussions are presented in Section 4. The last section summarizes the main research findings and proposes corresponding policy implications.

2. Literature review

2.1. Research on the BRI

The BRI aims to establish international cooperation strategies with other countries and strengthen regional trade and economic cooperation (Tukur, 2024). It connects a large number of developed and developing economies into an open and inclusive cooperation network (Qian et al., 2022). As a promising international cooperation platform, it has received widespread attention from governments, enterprises, and scholars worldwide (Ascensão et al., 2018). Since the proposal of the BRI, scholars have extensively discussed its reconstruction of the political and economic landscape of BRI countries, focusing on geopolitics (Poon et al., 2024), spatial responses (Petry, 2023), cross-border tourism (Quer and Andreu, 2023), education (Leskina and Sabzalieva, 2021), and environmental protection (Zhang et al., 2021). However, it has also raised doubts among some scholars in western countries, who believe that China's intention is to transfer some domestically high-pollution and energy-intensive industries through trade and investment in BRI countries and regions (Cai et al., 2018), thereby reducing domestic pollution emissions and environmental damage.

Regarding the environmental effects of the BRI, early studies primarily focused on the perspective of countries and regions along the route. Some studies treated BRI countries as a specific region and analyzed their carbon emissions, energy efficiency, and other characteristics based on different scales and perspectives (Chang et al., 2019). Other studies debated the "pollution haven" and "pollution halo" effects of foreign direct investment, discussing the environmental impact of China's foreign direct investment on BRI countries and regions. Some scholars have proven that China's foreign direct investment is green and low-carbon, and the implementation of the BRI has significantly reduced environmental pollution and improved green total factor productivity in BRI countries and regions (Hu et al., 2022; Xin and Wang, 2022), while many scholars also believed that the large-scale infrastructure investment and related industrial activities associated with the BRI posed environmental risks to host countries (Tian et al., 2019; Zhou et al., 2024). For example, Fang et al. (2021) argued while the BRI has made significant contributions to the rapid growth of cross-border trade, it has also led to the unintended transfer of resource extraction and environmental emission burdens to less developed countries. Similarly, the research results of Sattar et al. (2022) and Mpeqa et al. (2023) also indicated the BRI has a significant impact on environmental degradation.

2.2. Research on the EF

EF research serves as a method for assessing the environmental impact of human activities, spanning multiple scales including regional, national, and even global perspectives. Studies at different scales are crucial for understanding the environmental impact of human activities and formulating corresponding policies.

At the regional level, EF research primarily focuses on resource consumption and environmental impact in cities, communities, or specific geographical areas. For instance, Li et al. (2023) developed an urban agglomeration EF model and an extended nonlinear STIRPAT model to explore the spatiotemporal evolution and driving mechanisms of the EF in the Pearl River Delta. Pan and Guo (2023) constructed a Logarithmic Mean Divisia Index model to decompose the EF of the Yangtze River Economic Belt to identify key influencing factors. Wei et al. (2023) corrected the EF parameters based on net primary productivity and analyzed the status of ecological protection in the Yellow River Delta using the EF approach. Dai et al. (2023) analyzed the EF trends of Xiamen City and evaluated the sustainability of its development. Javeed et al. (2023) explored the relationship between economic growth, biocapacity, energy intensity, renewable energy, and EF in Asian countries. Hassan et al. (2023) studied the impact of nuclear energy, economic complexity, and globalization on the EF of OECD countries. These studies reveal the differences in resource consumption and environmental pressures across regions, providing robust support for regional sustainable development and facilitating cooperation and exchanges among regions to jointly address environmental challenges.

At the national scale, analysis of resource utilization and environmental impact based on countries emphasizes intercountry differences. For example, Wang et al. (2024b) investigated the impact of China's artificial intelligence development on the EF and explored its potential mechanisms. Fang et al. (2023) explored the impact of China's environmental policies from different EF perspectives. Wang et al. (2023a) studied the relationship between globalization, EF, innovation, and subjective well-being in OECD countries. Cutcu et al. (2023) focused on the relationship between the EF and foreign trade in the ten fastest-growing countries globally. Meanwhile, Ferreira et al. (2023) examined how various factors such as income sources, age, number of household members, and education level affect people's pressure on ecosystems in Portugal. Shen and Yue (2023) studied the nonlinear impact of the EF on biocapacity from different countries, providing a new perspective for assessing national sustainability. Scholars calculate the EF by analyzing energy consumption, land use, biodiversity conservation, and other conditions in various countries and assess their sustainable development capabilities. These studies play a vital role in formulating national environmental policies and promoting sustainable development.

At the global scale, the EF research focuses on global resource consumption and environmental pressure. These studies primarily use different statistical methods and models to explore the impact of economic growth, urbanization, industrialization, and other factors on the global ecological environment. For example, Quito et al. (2023) used quantile regression to explore the impact of industrialization, renewable energy, urbanization, and foreign direct investment on the global EF. Emmanuel et al. (2023) examined the impact of foreign capital, domestic capital formation, institutional quality, and democracy on the global EF. Cheng et al. (2024) investigated the impact of national logistics performance on environmental quality. In addition, Ullah et al. (2021) used threshold regression to focus on the nonlinear relationship between energy consumption, natural resource rents, and the EF. These studies emphasize the importance of sustainable development and environmental protection, as well as the environmental factors need to be considered in the process of economic growth and urbanization. Meanwhile, they also point out the need for countries to strike a balance between driving economic development and protecting the environment to achieve sustainable development.

The ecological footprint model has evolved over three decades and has become a key quantitative assessment tool for sustainable development. From the initial single land demand accounting to the current multi-dimensional innovations such as three-dimensional natural capital analysis, water footprint, and carbon footprint standardization, its methodology has been continuously improved (Cao and Zhang, 2016; Guo and Shen, 2017; Bastianoni et al., 2020). In terms of regional empirical studies, ecological footprint research has revealed the ecological constraints and unsustainable risks under different development models (Brizga, 2010; Deng and Wang, 2017; Li et al., 2022), which provides a scientific basis for designing differentiated sustainable development paths.

2.3. Research on influencing factors of the EF

With the continuous improvement of the concept and assessment methods of the EF, scholars at home and abroad have no longer limited their research to measurements, but have delved into the complex driving mechanisms behind it. EF, as an indicator for measuring human utilization of natural capital, is often influenced by various factors, which interact with each other to form complex driving mechanisms. These factors include economic growth (Li et al., 2023), population (Dasgupta et al., 2023), trade openness (Adebayo et al., 2024), urbanization (Udemba et al., 2024), and energy consumption (Khan et al., 2023). To find complex solutions, we have examined the relationships between these variables and the environment. The following is researches exploration of the relationships between the environment and these variables:

Economic growth has been proven to have a dual impact on environmental quality. On the one hand, some scholars believed that economic development can reduce the EF by improving efficiency and technological innovation, thereby reducing resource use and waste generation (Kihombo et al., 2021). Similarly, Tang et al. (2011) argued economic growth can enhance environmental awareness, technological innovation, and efficiency, thereby reducing environmental degradation. On the other hand, economic growth can increase the demand for natural resources and energy, leading to increased pollution and ecological damage (Çakmak and Acar, 2022). Furthermore, some studies suggested that there was a U-shaped relationship between economic growth and the environment (Ahmed et al., 2022). However, this hypothesis has been found to be uncertain in many studies, as the relationship between economic growth and environmental degradation is complex and influenced by various factors (Naseem et al., 2022). In addition, the actual impact of these channels may depend on country-specific factors (Acevedo-Ramos et al., 2023).

With increasing population, the demand for resources such as food, water, energy, and housing also increase, directly leading to an expansion of the EF. Regarding the impact of population size on the EF, the academic community generally believes that there is a significant positive correlation between them. Numerous studies, such as those by Li et al. (2021a), Yang and Hu (2018), and Wu (2020), have shown that population size is a major driving factor in the growth of the EF. Furthermore, Zhao et al. (2012) used the STIRPAT model to analyze and conclude that population size promoted the growth of the EF.

Energy consumption can have significant impacts on the EF through multiple channels. One of the most direct channels is the greenhouse gas emissions resulting from fossil fuel combustion, which is a major contributor to climate change and other environmental issues (Kazemzadeh et al., 2023; Baz et al., 2020). The use of natural resources, generation of waste, and environmental pollution are also influenced by energy consumption. Furthermore, the extraction and processing of fossil fuels can have substantial environmental impacts, such as water pollution and habitat destruction, which also contribute to an increase in the EF (Usman et al., 2022). In recent years, numerous studies have explored the complex relationships between energy consumption, economic growth, and environmental sustainability. Omer (2008) provided a comprehensive overview of this issue, emphasizing the need for sustainable energy to mitigate the negative environmental impacts of energy consumption. Similarly, Shahzad et al. (2021) highlighted the importance of reducing carbon emissions while maintaining economic growth. Usman and Makhdum (2021) pointed out as population growth and resource demand increase, so did the EF. Alola et al. (2019) emphasized the importance of renewable energy and sustainable development policies, while also highlighting the significance of sustainable economic growth patterns. Considering the need for sustainable economic growth, most countries have begun to focus on clean and renewable energy sources as the widespread use of non-renewable energy has been found to have high carbon intensity (Zaidi et al., 2018). Compared to non-renewable energy, renewable energy was less harmful to climate change and more cost-effective (Chen et al., 2019). In this regard, studies by Bhattacharya et al. (2017) and Inglesi-Lotz and Dogan (2018) had shown the use of renewable energy was relatively more environmentally friendly in the long run. Additionally, based on different types of renewable energy, some scholars have demonstrated the reducing effect of renewable energy consumption, such as solar and biomass energy, on the EF (Sharif et al., 2021).

The impact of urbanization on the EF can be categorized into four main aspects: land use, transportation, resource utilization, and waste management. As natural habitats were converted into urban areas, this may lead to losses in biodiversity and ecosystem services, but it also presented possibilities for more compact land use and conservation of natural ecosystems (Amer et al., 2022). The prevalence of high car ownership and usage rates in cities increased the risk of greenhouse gas emissions and air pollution, but it also offered opportunities for developing more sustainable transportation modes such as public transit and encouraging non-motorized travel (Glaeser et al., 2008). Urbanization may result in higher levels of resource consumption and waste generation, leading to resource depletion and increased waste production, but it can also provide opportunities for more efficient resource utilization and sustainable waste management practices (Nathaniel and Khan, 2020). With the continued growth of urban populations, the challenges posed by urbanization, including its impacts on environmental quality and the EF, are also increasing. Study by Cui et al. (2022) has shown the level of urbanization did indeed expand the EF. However, Liang et al. (2019) found promoting clean technologies and efficient transportation systems can reduce the EF. Some studies also indicated urbanization has both positive and negative impacts on the EF, depending largely on factors such as the level of economic development, availability of natural resources, and adoption of sustainable practices (Ahmed et al., 2020).

The impact of trade openness on environmental quality is a complex and controversial issue, with potential effects occurring through three theoretical channels. Firstly, the scale effect referred to the growth in economic activity and production resulting from trade liberalization, which may lead to higher levels of pollutant emissions and environmental degradation. This effect was particularly significant in emerging and developing economies, where environmental regulations were often weaker and the capacity to enforce such regulations was limited (Van Tran, 2020). Secondly, the composition effect involved changes in a country's economic structure due to trade liberalization, which may affect the types and levels of pollutants emitted by different sectors (Afesorgbor and Demena, 2022). Lastly, the technical effect suggested that trade openness can facilitate the transfer of knowledge and technology related to environmental management, thereby improving environmental quality (Tachie et al., 2020). Abdullahi et al. (2024) used long-term estimates to show trade openness had a significant positive impact on the EF. In contrast, other studies have found a negative correlation between trade openness and environmental quality. Al-Mulali and Ozturk (2015) discovered trade openness had a negative impact on environmental quality in the Middle East and North Africa region. Further research indicates the relationship between trade openness and environmental quality is more complex and influenced by other factors. For example, study by Abaidoo and Agyapong (2022) showed improving governance and regulatory structures help reduce carbon dioxide emissions associated with trade openness, thereby mitigating negative environmental impacts. Similarly, Zafar et al. (2019) found natural resources and human capital contribute to reducing the EF, as did foreign direct investment.

2.4. *Research gap*

Despite extensive research on the EF in the environmental field, this study aims to address scientific gaps. (1) Lack of comprehensive EF analysis in BRI sustainability research. While existing studies on the BRI focus narrowly on carbon emissions or isolated environmental metrics, this study pioneers the application of EF as a holistic indicator to systematically evaluate sustainability across BRI partner countries. This bridges a critical gap in understanding the BRI's integrated environmental pressure. (2) Absence of pan-Eurasian EF assessment. Prior EF research concentrates on specific regions (e.g., single nations or subcontinents), leaving Eurasia as a contiguous system critically understudied. This study fills this void by providing the first in-depth, continental-scale EF analysis spanning 83 countries from 2000 to 2022. (3) Inadequate dynamic sustainability measurement. Current sustainability assessments in Eurasia lack granularity in tracking natural capital dynamics. By introducing the three-dimensional ecological footprint model, this study innovatively quantifies the EFD and EFS, thereby offering a novel metric for diagnosing unsustainable development patterns. (4) Methodological limitations in causal inference. Traditional econometric methods fail to capture heterogeneous policy impacts. This study advances methodology by combining DID with quantile regression to reveal differential BRI effects across EF levels and conducting heterogeneity analysis to dissect impacts by sustainability type. (5) No unified framework for BRI's continental-scale impact. As the world's largest transnational development initiative, the BRI's ecological consequences demand analysis at a commensurate scale. This study is the first to integrate its effects on Eurasia's EF within a single empirical framework, setting a benchmark for assessing global sustainability policies. The novelty of this work lies in repositioning the EF from a static accounting tool to a dynamic sustainability diagnostic within the BRI context. By resolving these gaps, the study establishes EF as a core metric for BRI environmental governance, delivers actionable insights for achieving SDGs in resource-stressed regions, and provides a methodological blueprint for evaluating large-scale sustainability policies globally. Framework visualization as shown in Fig. 1.

3. Materials and methods

3.1. *Variables and data sources*

The dependent variable in this paper is the EF, with data sourced from the Global Footprint Network (https://www.footprintnetwork.org/). The core explanatory variable is the product of a dummy variable for countries participating in the BRI and a dummy variable for the implementation period of the BRI. The timing of each country's joining the BRI is obtained from China's Belt and Road website (https://www.yidaiyilu.gov.cn/datasearch.htm?1#china_macro). Due to missing EF values for 11 countries, this paper analyzes data from 83 countries in Eurasia spanning from 2000 to 2022, yielding a sample of 1909 observations, which include 64 countries and regions along the BRI. Control variables are selected based on theoretical analysis above, primarily comprising ecological carrying capacity (*EC*), per capita GDP (*AVGDP*), population (*P*), trade openness (*TO*), urbanization rate (*UR*), fossil fuel consumption (*TFC*), and renewable energy consumption (*REC*). Among these, *EC* data is sourced from the Global Footprint Network; *AVGDP*, *P*, *TO*, and *UR* data are from the World Bank; and *TFC* and *REC* data are from the U.S. Energy Information Administration. Given the large differences in the values of *EF*, *AVGDP*, *P*, and *EC*, these variables are logarithmic in the empirical analysis. Descriptive statistics for all variables are presented in Table 1.

3.2. *Methodology*

3.2.1. *Three-dimensional ecological footprint*

The two-dimensional ecological footprint method quantifies resource consumption across 6 different land types: cropland, forestland, grassland, water areas, built-up land, and fossil energy land, and then converts these into biologically productive land area. EC represents the biologically productive land area within a region can sustainably support human survival and development. To comprehensively evaluate the state of sustainable development, a two-dimensional ecological footprint model is used to conduct an in-depth comparative analysis of the *EF* and *EC*. The calculation formula is as follows:

$$EF = N \times ef = N \times \sum_{i=1}^{6} ef_i = N \times \sum_{i=1}^{6}\left(r_i \times \sum_{j=0}^{k}\frac{c_{ij}}{p_{ij}}\right) \tag{1}$$

$$EC = N \times \sum_{i=1}^{6}(\alpha_i \times r_i \times y_i) = N \times \sum_{i=1}^{6}\left(\frac{s_i}{N} \times r_i \times y_i\right) \times (1 - 12\%) \tag{2}$$

where *EF* represents the ecological footprint value of a specific region (ha); *N* is the population of the specific region (cap); *ef* is the per capita ecological footprint (ha/cap), with *i* denoting one of the 6 land types; r_i is the equivalence factor for the i_{th} type of biologically productive land; c_{ij} is the per capita annual consumption of the j_{th} product on the i_{th} type of biologically productive land (kg/cap); p_{ij} is the global average yield per unit area of the j_{th} product on the i_{th} type of biologically productive land (kg/ha); *EC* is the ecological carrying capacity of the specific region (ha); a_i is the per capita area of biologically productive land; y_i is the yield factor for the i_{th} land use type; and s_i refers to the area of the i_{th} type of land (ha). Notably, when calculating the *EC*, 12% is deducted as a protected area for biodiversity within the ecosystem.

The essence of the EF is to represent the degree of occupation of the ecological environment by human resource consumption

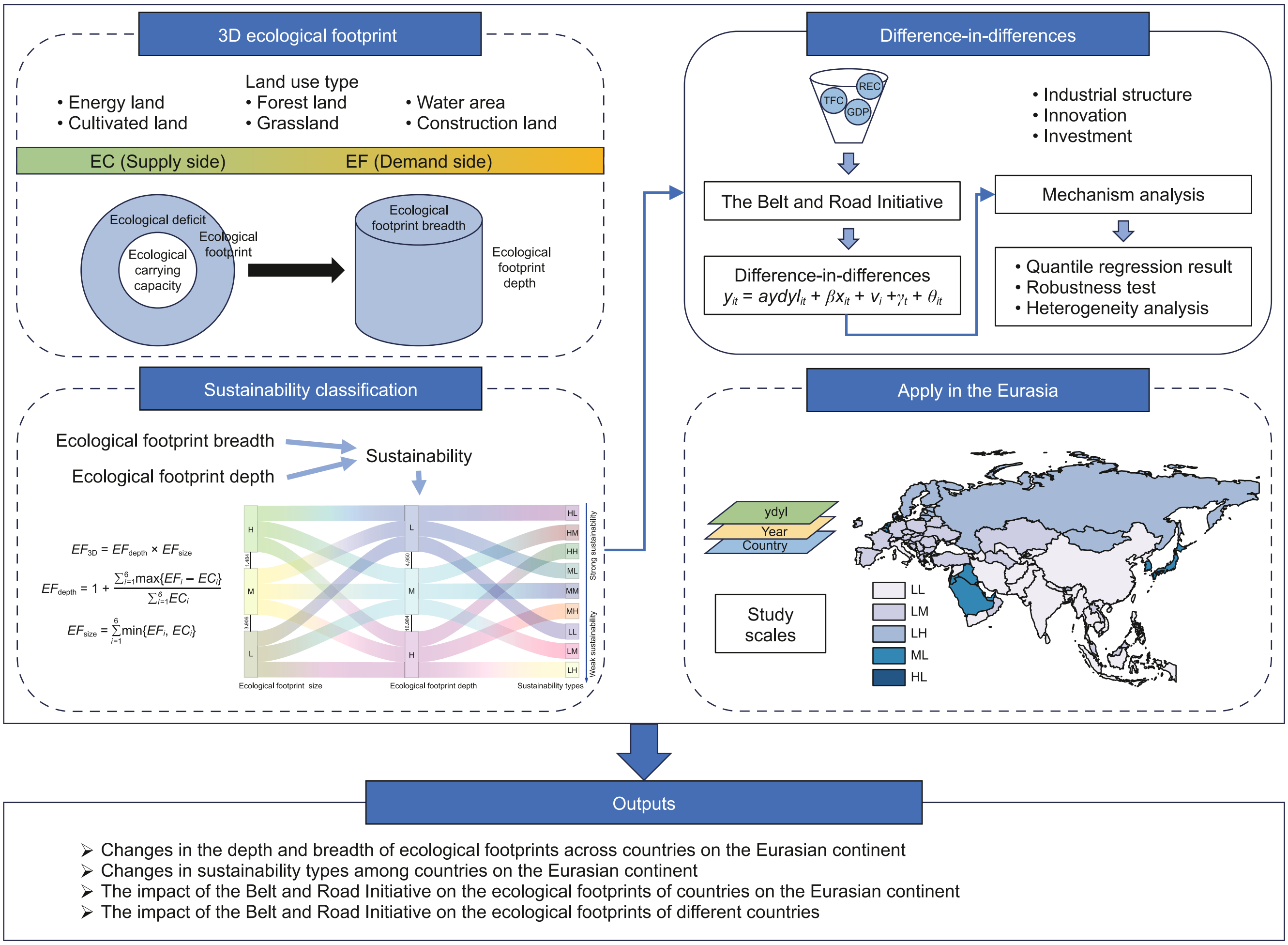


Fig. 1. The conceptual framework.

Table 1
Descriptive statistics of variables.

Variables	Unit	Observation	Mean	Standard deviation	Minimum	Maximum
ln *EF*	ha	1909	17.391	1.569	12.559	22.386
National characteristic variables						
ln *AVGDP*	USD	1909	9.757	9.947	4.921	11.803
ln *P*	cap	1909	16.231	1.679	12.719	21.072
TO	%	1909	98.210	58.959	3.762	437.327
UR	%	1909	62.475	21.248	13.397	100.000
Ecological characteristic variables						
ln *EC*	ha	1909	16.521	1.744	12.196	22.386
TFC	10^{15} Btu	1909	3.607	12.255	0.000	159.676
REC	10^{15} Btu	1909	0.129	0.538	0.000	9.999

using an area measurement, which is a two-dimensional concept (Fig. 2). It does not make a substantive distinction between stock and flow. The three-dimensional ecological footprint model introduces two parameters: EFD and EFS, which are used to quantify the consumption of natural resource stock and flow. EFD indicates the multiple of land required to maintain current resource consumption per unit area, while EFS reflects the extent to which humans utilize the flow of natural capital within the EC. The calculation formulas for the aforementioned parameters are as follows.

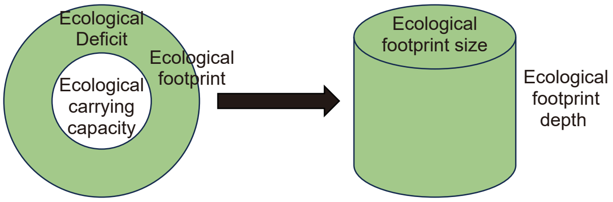


Fig. 2. Development of the ecological footprint models from two-dimensional to three-dimensional.

$$EF_{3\mathrm{D}} = EF_{\mathrm{depth}} \times EF_{\mathrm{size}} \tag{3}$$

$$EF_{\mathrm{depth}} = 1 + \frac{\sum_{i=1}^{6} \max\{EF_i - EC_i\}}{\sum_{i=1}^{6} EC_i} \tag{4}$$

$$EF_{\mathrm{size}} = \sum_{i=1}^{6} \min\{EF_i, EC_i\} \tag{5}$$

where $EF_{3\mathrm{D}}$ represents the three-dimensional ecological footprint (ha); EF_i is the EF of the i_{th} land use type (ha); EC_i is the EC of the i_{th} land use type (ha); EF_{depth} is the EFD. When $EF_{\mathrm{depth}} \leq 1$, it indicates the flow of natural capital in the region is sufficient to meet human needs; otherwise, it indicates the region is in an unsustainable state of development (Niccolucci et al., 2011). EF_{size} represents the EFS (ha).

3.2.2. Difference-in-differences model

One of the purposes of this paper is to study how the BRI affects the EF of countries across Eurasia. To address the endogeneity issues among the research variables, this paper employs the DID method, using the BRI proposed in 2013 as a quasi-natural experiment. The DID method can address the endogeneity issue among various research variables, eliminate the influence of other variables on the dependent variable, and isolate the “net effect” of the BRI on the ecological footprints of various countries. Therefore, this paper employs the DID method. The first level of difference is at the national level, dividing Eurasian countries into 64 countries which joined the BRI before 2022 and other countries did not join. The second level of difference is at the temporal level, with the BRI proposed in 2013, serving as the dividing point between the periods before and after 2013. The specific econometric model is as follows:

$$y_{it} = \alpha ydyl_{it} + \beta x_{it} + \nu_i + \gamma_t + \theta_{it} \tag{6}$$

$$ydyl_{it} = \mathrm{country}_i \times \mathrm{year}_t \tag{7}$$

In Eq. (6), a DID estimation model is employed, considering both time and country fixed effects. y_{it} represents the *EF*. The core variable of coefficient α captures the impact of the BRI on the EF of each country. $ydyl_{it}$ is the interaction term between the dummy variable and the treatment group dummy variable, used to estimate the effect of the BRI. x_{it} is a set of time-varying characteristic variables for Eurasian countries. ν_i represents the country fixed effect, γ_t denotes the time fixed effect, and θ_{it} is the random error term. $\mathrm{country}_i$ is the treatment group dummy variable, assigned a value of 1 for countries joined the BRI before 2022 and 0 otherwise. year_t is the treatment effect time dummy variable, assigned a value of 1 for years after 2013 and 0 for years up to and including 2013.

4. Results and discussions

4.1. Spatial-temporal dynamic analysis of EF and EC

4.1.1. Ecological footprint

As shown in Fig. 3, Eurasia's per capita ecological footprint rose from 2.147 ha/cap to 2.570 ha/cap. Significant differences exist between Asia and Europe: Asia maintained a footprint below Eurasia's average (1.858 ha/cap to 2.284 ha/cap), though mirroring the overall upward trend. Europe recorded footprints approximately double Eurasia's average. Despite this, Europe achieved a 13.3% reduction amid fluctuations, indicating improved resource sustainability.

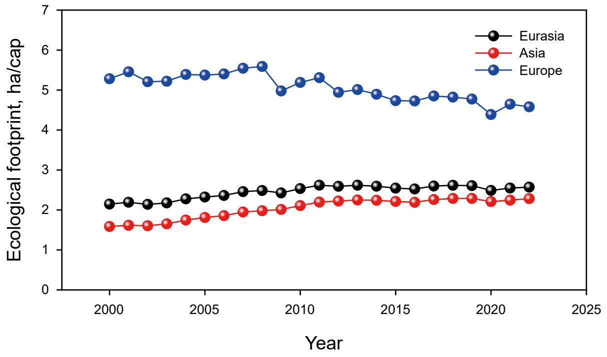


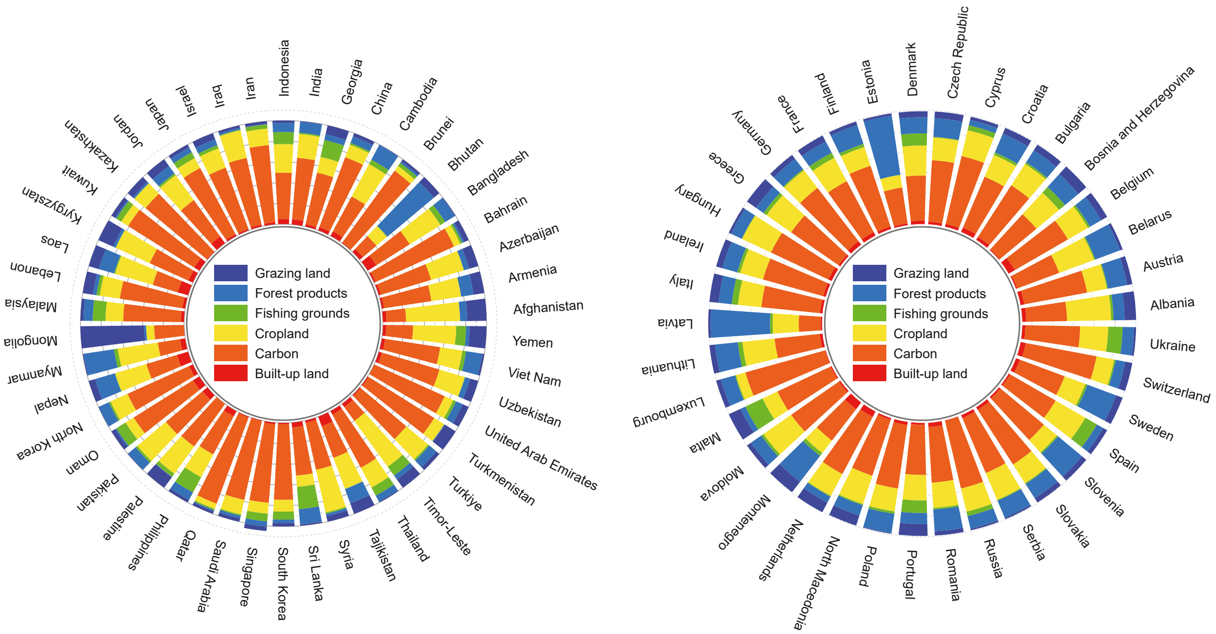
Fig. 3. Spatio-temporal evolution of ecological footprint in Eurasia from 2000 to 2022.

Asia and Europe show a similar ordering of resource types in their per capita ecological footprints (Fig. 4(a) and (b)). Both are dominated by fossil energy land (Asia 53.69%; Europe 49.98%) and cropland (Asia 23.07%; Europe 22.16%), with other land types comprising 27.86% in Europe. Notable exceptions include Mongolia (grassland 61.46%; fossil energy 28.76%), Bhutan (forestland and fossil energy>75%), Georgia and Sri Lanka (higher water proportion than cropland), while Estonia and Latvia both exceed 50% forestland, and Montenegro also maintains a high forestland share.

From 2000 to 2022, Asia's per capita ecological footprint showed significant regional disparities (Fig. 5), ranked in descending order as: South Asia (0.878 ha/cap) < Southeast Asia (1.664 ha/cap) < Central Asia (2.718 ha/cap) < West Asia (2.928 ha/cap) < East Asia (3.196 ha/cap). South Asia's steadily rising footprint reflects its low economic development, according to World Bank, South Asia's per capita GDP is only USD 2308.72, far below the global average of USD 13138.3. Southeast Asia's footprint nearly doubled South Asia's but remained below regional highs, indicating varying resource consumption intensities requiring tailored approaches. Central and West Asia showed volatile “increase-decrease” patterns, with West Asia's prolonged conflicts and Central Asia's sparse population limiting their contributions. East Asia emerged as the primary contributor (70.15% overall increase), driven by dense populations, rapid economic growth, urbanization, and industrialization which elevated resource demands.

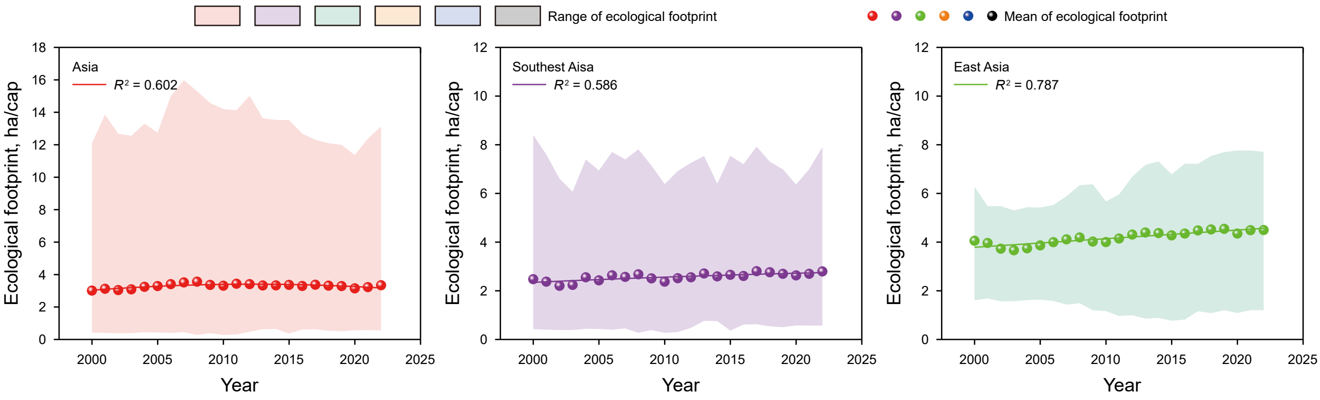
Europe's per capita ecological footprint showed an overall decline from 2000 to 2022 (Fig. 6), contrasting with Asia's trend, with regional rankings as follows: Southern Europe (4.432 ha/cap) < Central Europe (5.057 ha/cap) < Eastern Europe (5.101 ha/cap) < Western Europe (5.780 ha/cap) < Northern Europe (6.601 ha/cap). Northern Europe recorded the largest decrease (21.18%), attributed to strong environmental policies prioritizing sustainability (Georgescu and Kinnunen, 2024). Southern and Western Europe showed smaller, stable declines despite their economic development and urbanization, constrained by consumption patterns. Central Europe's minimal reduction likely reflects its heavy industry base. Notably, Eastern Europe exhibited a counter-trend increase, potentially due to prioritizing economic growth over environmental protection during development, alongside less stringent policies.

Using the natural breaks classification, Eurasia's 83 countries were categorized by mean per capita ecological footprint into low (0.473–2.313 ha/cap), medium (2.314–7.363 ha/cap), and high (7.634–13.844 ha/cap) levels. Significant footprint variations from

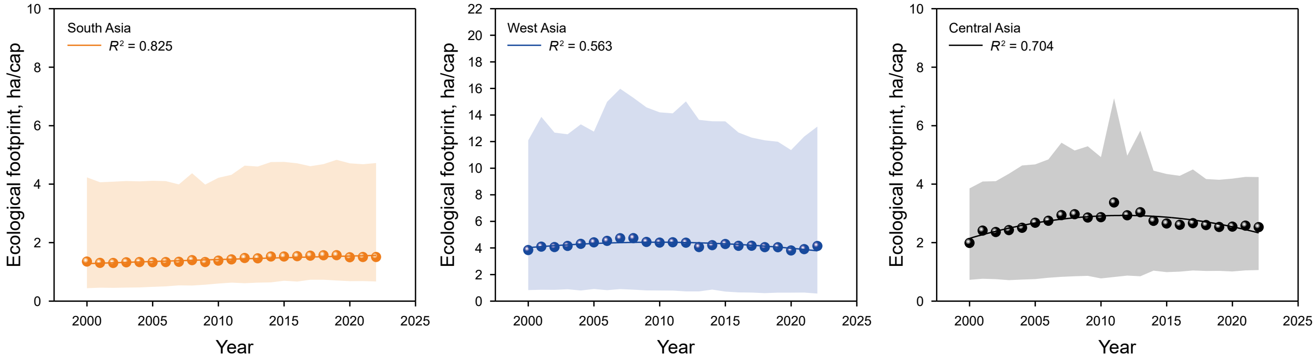


(a) Asia **(b)** Europe

Fig. 4. Composition of per capita ecological footprint in Eurasia from 2000 to 2022.



(a) Asia **(b)** Southest Aisa **(c)** East Asia

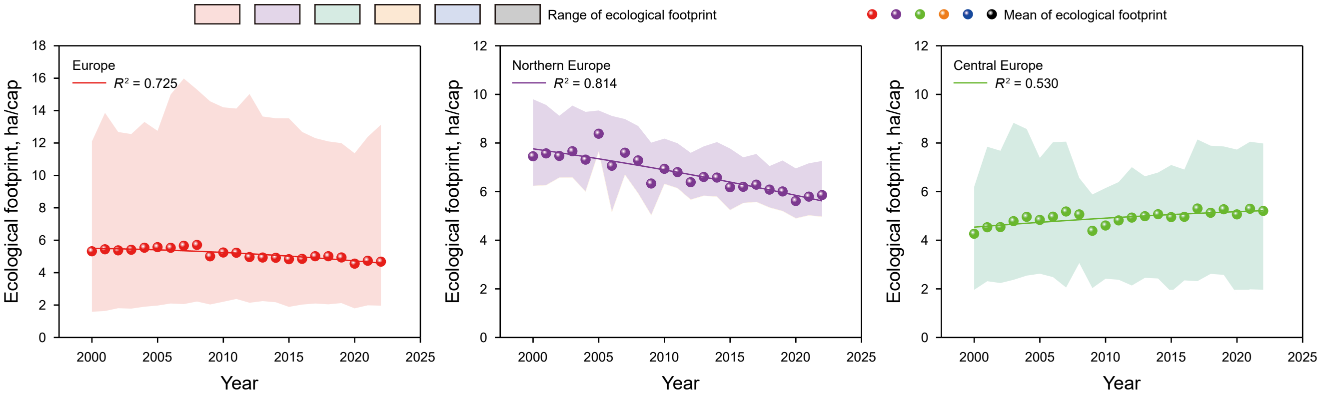


(d) South Asia **(e)** West Asia **(f)** Central Asia

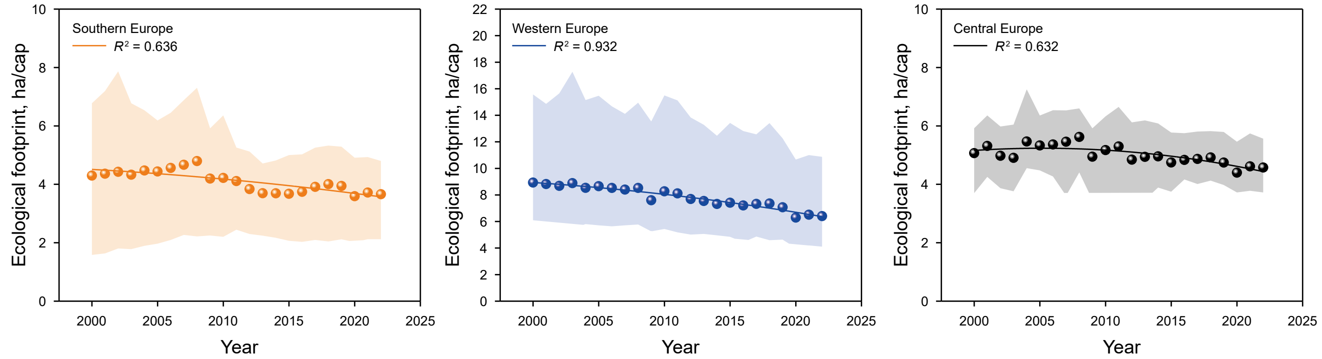
Fig. 5. Range and mean of per capita ecological footprint by region in Asia from 2000 to 2022.

2000 to 2022 occurred predominantly in Asia (Fig. 7), with notable transitions in China, Kazakhstan, Thailand, and Vietnam (low→medium), Uzbekistan (medium→low), and Mongolia (medium→high). While over 80% of countries ranked low in 2000 (only a few medium), by 2022 most exceeded medium levels, with low-level countries concentrated mainly in South and Southeast Asia.

Compared to Asia, only a few countries in Europe experienced changes in their per capita ecological footprint levels. Most



(a) Europe **(b)** Northern Europe **(c)** Eastern Europe



(d) Southern Europe **(e)** Western Europe **(f)** Central Europe

Fig. 6. Range and mean of per capita ecological footprint by region in Europe from 2000 to 2022.

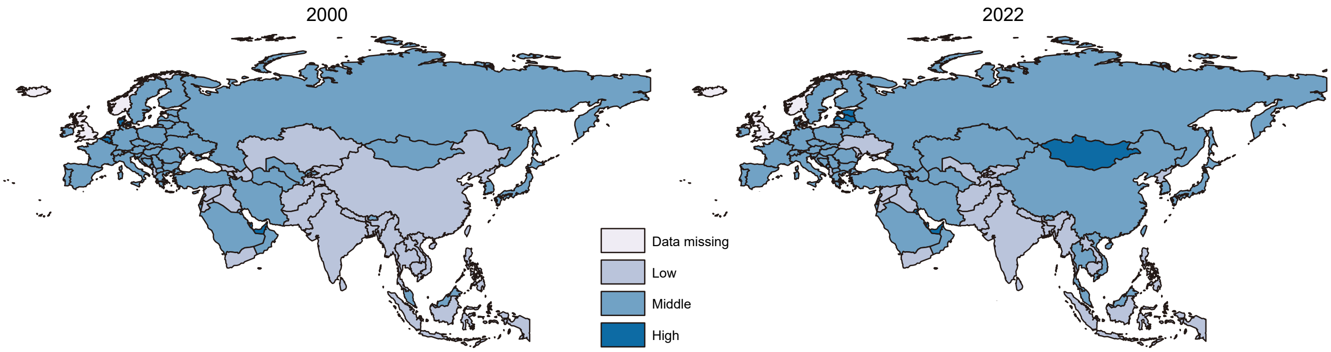
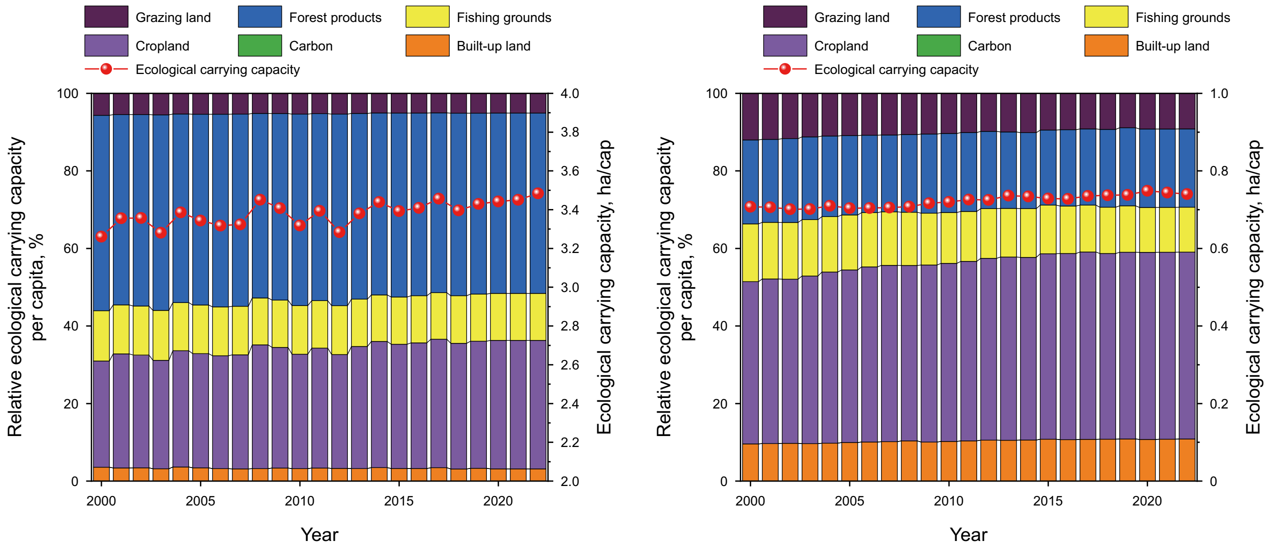


Fig. 7. Spatial-temporal evolution of per capita ecological footprint in Eurasia from 2000 to 2022.

notably, Ukraine's per capita ecological footprint shifted from medium to low levels. Similarly, Denmark and Belgium saw their per capita ecological footprint decline from high to medium levels. As mentioned earlier, the reasons for these changes differ. Ukraine's decline was influenced by war and political instability, while Denmark and Belgium's reduction was due to the implementation of a series of environmental policies and measures that reduced natural resource use and emissions, for instance, Denmark passed a bill in 2024 to impose taxes on livestock emissions. The tax revenue is used to fund the green transformation of farms and establish a 400 million kroner fund to support ecological restoration. Belgium has also established the first polyethylene terephthalate recycling chain. Both countries have reduced the use of natural resources and emissions, resulting in a decrease in the per capita ecological footprint. Additionally, a few countries, such as Estonia and Latvia, experienced an increase in their per capita ecological footprint levels. Overall, Europe countries' per capita ecological footprint levels remained relatively stable from 2000 to 2022, with over 90% of countries at the medium level.

4.1.2. Ecological carrying capacity

From 2000 to 2022, the per capita ecological carrying capacity of Eurasia showed an overall stable upward trend (Fig. 8), increasing from 3.969 ha/cap in 2000 to 4.224 ha/cap in 2022. During the study period, the trend in per capita ecological carrying capacity in Asia was consistent with that of Eurasia, rising from 0.708 ha/cap in 2000 to 0.740 ha/cap in 2022. In Europe, the per capita ecological carrying capacity increased amidst fluctuations, from 3.261 ha/cap in 2000 to 3.484 ha/cap in 2022, contributing



(a) Europe **(b)** Asia

Fig. 8. Spatio-temporal evolution of ecological carrying capacity in Asia and Europe from 2000 to 2022.

approximately 82% to the overall per capita ecological carrying capacity of Eurasia. Specifically, although the per capita ecological carrying capacity in both Asia and Europe exhibited an increasing trend, the difference between them was significant, with Europe's per capita ecological carrying capacity being roughly 4–5 times that of Asia, maybe due to Europe's relatively mild climate conditions and abundant water resources, as well as its more developed industries and technologies in agriculture, forestry, and fisheries. In contrast, Asia has diverse climatic conditions, ranging from cold Arctic regions to hot tropical areas, and some countries may face environmental issues such as water scarcity, land desertification, and biodiversity loss. In some areas, such as the eastern coastal regions of China and the Indus Plain in South Asia, the dense population, high level of industrialization, and frequent agricultural activities may also exert considerable pressure on ecosystems.

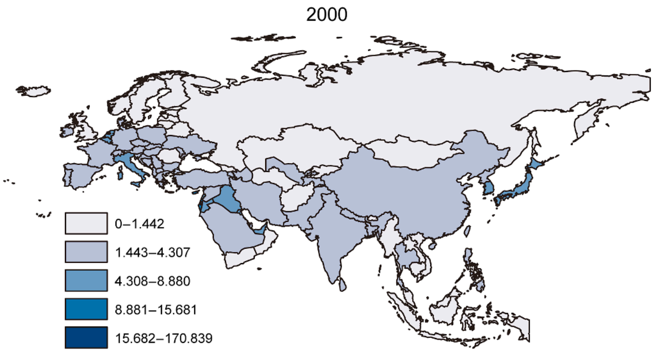
In terms of the composition of land types for per capita ecological carrying capacity, from 2000 to 2022, Asia's per capita ecological carrying capacity was primarily composed of cropland (46.03%) and forestland (20.31%), with relatively smaller proportions of water areas, built-up land, and grassland, totaling 33.66%. Compared to Asia, the top three land types contributing to Europe's per capita ecological carrying capacity were forestland (48.18%), cropland (30.91%), and water areas (12.36%). Regarding the trends in the proportions of various land types, cropland in Asia showed a significant increase, while water areas and grassland decreased to some extent, with forestland and built-up land remaining relatively stable. The proportions of per capita ecological carrying capacity from forestland, cropland, and water areas in Europe remained stable with minor fluctuations during the study period, while grassland and built-up land showed no significant changes.

4.2. *Analysis of the EFD and EFS*

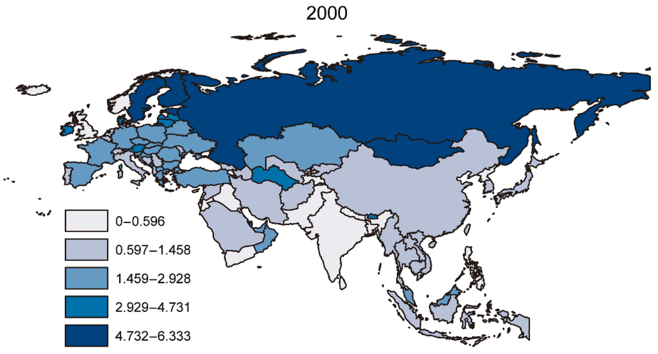
From the perspective of Eurasia as a whole, the EFD has continuously risen from 1.966 ha/cap in 2000 to 2.513 ha/cap in 2022, indicating that the unsustainable development situation in this region was deteriorating (Fig. 9(a)). Meanwhile, the utilization rate of natural capital flows in Eurasia also exhibited a declining trend from 2000 to 2022, with the per capita EFS slightly decreasing from 1.092 ha/cap to 1.023 ha/cap (Fig. 9(b)).

In terms of continents, both Asia and Europe had EFD values exceeding the threshold of 1, indicating that they were currently in a state of unsustainable development. Upon further comparison, it was found that Asia's EFD was significantly higher than that of Europe. In 2022, Europe's EFD was only 1.315 ha/cap, while Asia's EFD reached 3.394 ha/cap, nearly 2.6 times that of Europe. On the other hand, based on the average per capita EFS, it can be seen that compared to Europe, Asia has relatively scarce resources, with less flow capital available for development. In 2022, Europe's per capita EFS was 3.484 ha/cap, while Asia's per capita EFS was only 0.673 ha/cap. This study also reveals an interesting phenomenon, namely, there is a complementary relationship between per capita EFS and EFD.

From a national perspective, this study found that Italy, Ukraine, Saudi Arabia, Syria, Turkmenistan, and Singapore exhibited the most significant changes in the EFD (Fig. 10(a)). Specifically, Saudi Arabia, as one of the world's largest oil producers, consumes a vast amount of energy and water resources during oil extraction and processing, while generating a substantial amount of waste and emissions, which directly led to a marked increase in its EFD. Similarly, political instability and economic isolation have constrained Turkmenistan's efforts in environmental protection and sustainable development. Coupled with the rapid development of the oil and gas industry, it has resulted in over-exploitation and utilization of natural resources, thereby exacerbating the EFD. Conversely, Italy, Ukraine, Syria, and Singapore have shown a decreasing trend in EFD. Italy has adopted climate policies such as reducing greenhouse gas emissions and improving energy efficiency, and actively promoted economic structural transformation to reduce dependence on natural resources and ecological pressure. Wars and political unrest in Ukraine and Syria have led to a reduction in economic activities, particularly the extraction and utilization of natural resources, thereby lowering the EFD to some extent. Notably, Singapore has seen the most significant reduction in the EFD, from 170.84 ha/cap in 2000 to 55.11 ha/cap in 2022, primarily due to effective water resource management measures that have significantly improved water self-sufficiency. Additionally, Singapore is committed to



(a) Ecological footprint depth



(b) Per capita ecological footprint size

Fig. 9. Per capita ecological footprint size and depth in Eurasia from 2000 to 2022.

(a) Ecological footprint depth

(b) Per capita ecological footprint size

Fig. 10. Per capita ecological footprint depth and size of different countries in Eurasia from 2000 to 2022.

improving energy efficiency, promoting renewable energy, and formulating strict environmental protection policies and regulations, successfully reducing its EFD.

In terms of per capita EFS, for most countries, human occupation of natural capital flows has remained stable, but there were significant differences among some countries (Fig. 10(b)). Among these countries, France, Austria, Romania, Belarus, Kazakhstan, Myanmar, and Thailand have experienced notable increases in per capita EFS, indicating an improvement in the level of utilization of flow capital in these regions. In 2022, Estonia, Mongolia, Latvia, and Russia ranked among the top in per capita EFS, benefiting from abundant natural resources, providing a solid foundation for sustainable development. Specifically, Estonia has a forest cover rate of about 50%, with rich timber reserves, and its per capita EFS is mainly composed of forest resources. As a renowned natural pasture, Mongolia's grassland resources provide extensive space for its livestock industry, which is also an important part of its per capita EFS. Latvia similarly boasts abundant forest resources, contributing to its ecological environment and biodiversity. Russia is one of the countries with the richest forest resources in the world, with forest area covering more than 50% of its land area and the world's largest timber reserves. Furthermore, it has vast grasslands and cropland resources, providing a solid foundation for Russia's ecological environment.

4.3. National sustainability classification

The depletion of natural capital stock and the utilization of natural capital flows are core issues in assessing sustainability. To quantify these two aspects specifically, the three-dimensional ecological footprint model introduces two indicators: EFD and EFS, which represent the consumption of natural resource stocks and the utilization of flows. The sustainability level of a country can be measured to some extent by these two indicators. In this study, we calculated the average EFD and average per capita EFS for each country in Eurasia from 2000 to 2022, and used the natural breaks classification method to divide both indicators into three levels: low (L), medium (M), and high (H). The breakpoints for the EFD were 4.950 and 16.984, and for per capita EFS were 1.484 and 3.906. Based on this classification, we further adopted a 3×3 matrix classification method to categorize 83 countries into 9 different types of sustainable development, including low size-high depth (LH), low size-medium depth (LM), low size-low depth (LL), medium size-high depth (MH), medium size-medium depth (MM), medium size-low depth (ML), high size-high depth (HH), high size-medium depth (HM), and high size-low depth (HL). Among these types, countries with larger per capita EFS tend to have better sustainability, while countries with deeper EFD tend to have poorer sustainability. Therefore, countries of the LH type perform the worst in terms of sustainability, while those of the HL type exhibit the strongest sustainability.

As shown in Fig. 11, in 2000, Eurasia exhibited 6 different types of sustainable development, with the three types of LM (covering 24 countries), LL (covering 32 countries), and ML (covering 14 countries) being the most common. In 2022, the types of sustainable development in Eurasia decreased, with the MM type disappearing, while LM (expanded to 27 countries), LL (decreased to 30 countries), and ML (expanded to 15 countries) still dominated. The main reasons lie in the systemic imbalance caused by extreme climate conditions and geopolitical conflicts. The century-long drought on the Eurasian continent has led to excessive groundwater extraction for agriculture, such as a 18% reduction in French wheat production. The conflict between Russia and Ukraine has cut off gas supplies, forcing Germany's coal power generation share to rise from 28% to 33%. The deepening fossil fuel footprint has occurred. After the COVID-19 pandemic, high-carbon recovery has increased resource consumption. The industrial land expansion in Vietnam has increased by 20%, and new coal power projects have been approved in western China, resulting in a general increase in the footprint depth of the original MM countries. The breadth has polarized due to economic contraction or expansion. Ultimately, they collectively slide towards a high-depth (MH type) or low-breadth (ML type) state.

After an in-depth analysis spanning these 23 years, the study found that the sustainability of 6 countries declined, while 6 others made progress in this regard (Fig. 12). Overall, Asia exhibited weaker sustainability, primarily manifested in the LL, LM, and LH types. Among these, countries with stronger sustainability were mainly distributed in Northern Asia and Western Asia, represented by the LH and ML types. Specifically, Northern Asia was dominated by the LH type, with countries showing relatively stable sustainability throughout the study period. In contrast, some countries in Western Asia had significantly improved their sustainability through green renovations, agricultural technological revolutions, circular economy, and waste management methods, such as Saudi Arabia, which jumped from the LL type to the ML type.

Compared to Asia, Europe's sustainable situation was more optimistic, with sustainable development types mainly manifesting as LM and LH. Among these, LM was concentrated in Southern Europe, Central Europe, and some Western Europe countries, while Eastern Europe and Northern Europe were primarily dominated by the LH type. Notably, Italy's sustainable development situation had deteriorated markedly, shifting from the ML type to the LL type. Possible reasons include sluggish economic growth, failure to transform the industrial structure, fiscal pressure from high welfare policies, and deterioration in terms of trade due to rising international energy prices and fluctuations in the euro exchange rate.

4.4. Difference-in-differences result

4.4.1. Baseline regression

This section examines whether the implementation of the BRI has affected the changes in the EF of Eurasian countries. Based on the specification of Eq. (6), this paper tests the changes in the EF resulting from the implementation of the BRI, with the results presented in Table 2. Column (1) controls for country fixed effect

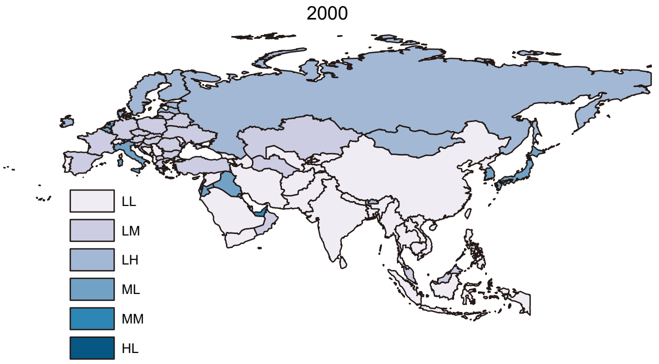


Fig. 11. Sustainable development types in Eurasia from 2000 to 2022.

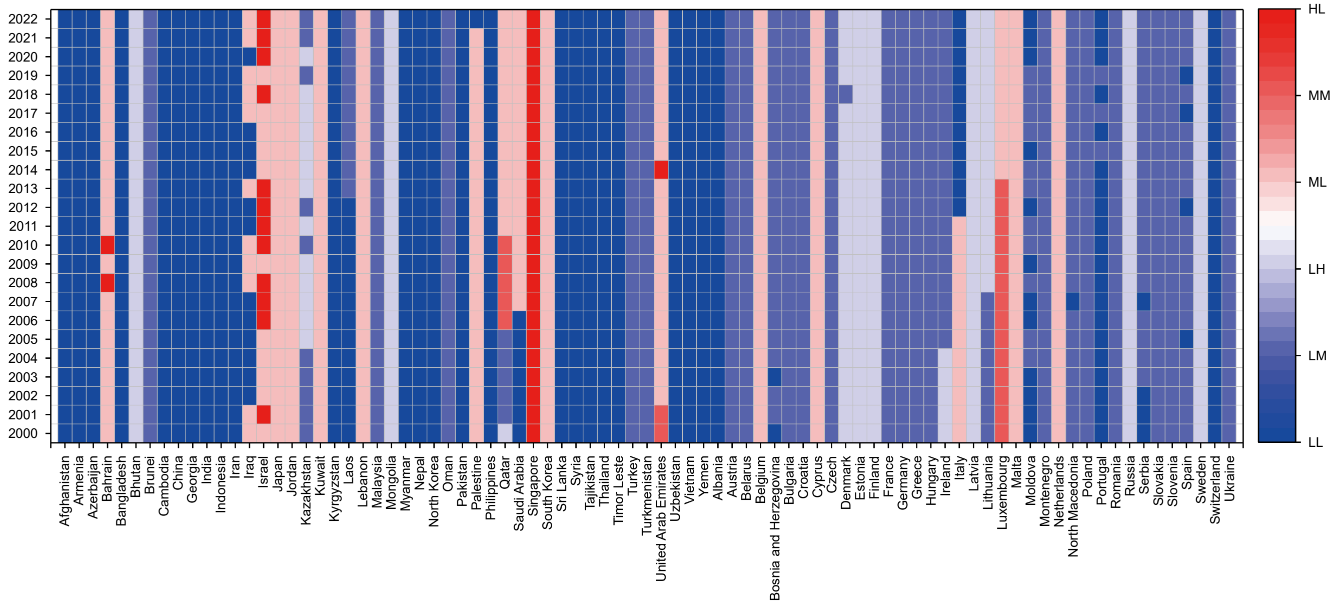


Fig. 12. Sustainability heatmap of Eurasia from 2000 to 2022.

and time fixed effect. Column (2) further controls for national characteristic variables on this basis, while Column (3) additionally controls for ecological characteristic variables. The study finds all regression coefficients are positive and significant at the 1% level. According to the estimation results in Column (3), it is found that the BRI has a significant positive impact on the EF of Eurasian countries. By promoting infrastructure construction, energy cooperation, and financial cooperation, the BRI has facilitated economic development in countries along the route, most of which are developing countries. Economic development is often accompanied by increased resource utilization, thereby expanding the EF to some extent.

4.4.2. Mechanism analysis

To explore how the BRI affects the EF of Eurasian countries, this paper draws on previous research and finds industrial structure, technological progress, and foreign direct investment can influence the EF (Dong et al., 2020; Li et al., 2021b; Udemba et al., 2024). Specifically, an increase in the proportion of industry within the industrial structure leads to environmental degradation, while an increase in the proportion of the service sector improves environmental quality (Wang et al., 2023b; Lu and Wang, 2024). In the long run, changes in the industrial structure led to a gradual shift in production processes from simple low-tech activities to more advanced manufacturing techniques. However, in the short term, when the industrial structure is mainly composed of resource-intensive and labor-intensive industries, the expansion of economic activities may result in an increase in fossil fuel consumption and pollutant emissions (Wang et al., 2023a). Meanwhile, an industrial structure composed of knowledge-intensive and technology-intensive industries is more conducive to reducing pollutant emissions. There is a significant positive correlation between foreign direct investment and the EF (Muhammad et al., 2021; Zafar et al., 2019; Ponce et al., 2022). Foreign direct investment promotes a country's economic growth by enhancing productivity, capital accumulation and technology dissemination. Therefore, most developing countries are eager to attract foreign direct investment (Seker et al., 2015). Although Foreign direct investment has significant potential to promote economic growth, if industries from developed countries with strict environmental standards are transferred to developing countries with lower environmental standards, it may also harm environmental quality (Chandran and Tang, 2013). Thus, foreign direct investment is regarded as another determinant of environmental degradation. Technological progress has a significant negative correlation with the EF (Lu and Wang, 2024; Raihan, 2023; Pata and Erdogan, 2025).

Therefore, this paper adopts industrial structure, technological innovation, and foreign direct investment as mediating variables. Among them, industrial structure is measured by the ratio of the value added of the secondary industry to the value added of the tertiary industry, and technological innovation is represented by

Table 2
Baseline regression results.

	(1)	(2)	(3)
Dependent variables	ln *EF*	ln *EF*	ln *EF*
$ydyl_{it}$	0.215*** (0.053)	0.206*** (0.038)	0.160*** (0.040)
Constant	17.214*** (0.027)	3.612** (1.665)	−2.171* (2.561)
Country fixed effect	Yes	Yes	Yes
Time fixed effect	Yes	Yes	Yes
National characteristic variables	No	Yes	Yes
Ecological characteristic variables	No	No	Yes
Sample size	1909	1909	1909
R^2	0.803	0.895	0.903

Note: *, **, *** indicate significance at the 10%, 5%, and 1% levels, respectively. Standard errors are in parentheses.

the number of new patents in each country. Data on the value added of the secondary and tertiary industries and foreign direct investment are sourced from the World Bank, while patent data are obtained from the WIPO Statistics Database. Since the three-stage mediation model is prone to endogeneity issues, this paper follows the research by Jiang (2022) to conduct a two-stage mediation variable test, constructing Eq. (8)

$$Med_{it} = \alpha ydyl_{it} + \beta x_{it} + \nu_t + \gamma_t + \theta_{it} \tag{8}$$

where Med_{it} represents the mediating variable, which stands for industrial structure, technological innovation, and foreign direct investment, with the rest of the variables consistent with those mentioned above.

The specific results are shown in Table 3, which indicates that the BRI indirectly affects the EF by influencing industrial structure, technological innovation, and foreign direct investment. That is, the BRI drives an increase in the value added of the secondary industry and net foreign investment in various countries, leading to an increase in their EF, while promoting a decrease in the EF by increasing the number of patents. The industrial structure adjustment under the BRI achieves this through infrastructure expansion, energy transition, and capacity transfer. In the short term, it increases the EF, particularly in terms of land occupation, resource extraction, and cross-border pollution transfer. The BRI has a negative impact on the EF of the participating countries through foreign direct investment. Infrastructure expansion and industrial transfer directly increase ecological pressure. For instance, transportation and energy projects occupying land led to the fragmentation of biological habitats, and resource-extraction-based industries increase the consumption of natural capital. At the same time, the cross-border transfer of high-energy-consuming industries and traditional energy projects further expand carbon emissions and land disturbance. The BRI significantly reduces the EF of the participating countries through technological innovation. For example, the Adama Wind Farm in Ethiopia has cumulatively reduced carbon dioxide emissions by 2158 tons. China's wind and solar power products exported in 2022 contributed approximately 41% of the global carbon emission reduction from renewable energy. The United Arab Emirates introduced the Chinese intelligent washing system to restore petroleum hydrocarbon contaminated soil, achieving a removal rate of 92.3%.

4.4.3. Quantile regression result

After exploring the mechanisms through which the BRI affects the EF of various countries, considering the uneven social, economic, and ecological development among Eurasian countries with significant differences, this paper further employs a quantile regression approach in addition to the DID method to better assess the impact of the BRI on the EF of countries along the route. By analyzing the variation in treatment effects across different quantiles, we aim to gain a more comprehensive understanding of the policy's impact on the EF of different countries.

Quantile regression is a method performing regression analysis on the independent variable X through conditional quantiles to obtain regression models for all quantiles. Drawing on the research by Wan et al. (2021), this paper selects the 0.2, 0.4, 0.6, and 0.8 quantiles for explanation and illustration. The data in Table 4 show the coefficients of $ydyl_{it}$ are positive and significant at all quantiles, indicating that the BRI promotes the EF of countries, and the promotion effect is more pronounced in countries with lower EF. The reasons for this might lie in the fact that many countries with low EF are developing countries, whose energy structure has long relied on fossil fuels, and whose industrial technologies are outdated. The unit energy consumption and pollution emissions per GDP are also relatively high. The BRI helps these countries directly skip the traditional high-pollution development stage by exporting renewable energy technologies. Moreover, these low EF countries often lack strict environmental regulatory systems. The green standards and norms promoted by BRI directly enhance their environmental governance capabilities.

4.4.4. Heterogeneity analysis

Based on the previous analysis, there are significant differences in both EFD and per capita EFS among Eurasian countries, and their sustainability also varies, which may lead to different impacts on the EF changes. To verify whether these impacts truly exist, this paper examines through EFD, per capita EFS, and sustainability types. EFD and per capita EFS among Eurasian countries are divided into low, medium, and high types in Section 4.2. Due to the small number of countries with high EFD and per capita EFS, it is difficult to draw commonalities in their impacts. Hence, the countries in the medium and high types are combined, resulting in two categories for the EFD: low and medium-high, and two types for per capita EFS: low and medium-high. From the perspective of sustainability, Eurasia encompasses 6 types of sustainable countries in Section 4.3. Based on the previous conclusions, LL, LM, and LH are classified as weak sustainability, while ML, MM, and HL are classified as strong sustainability. The results in columns (1) and (2) of Table 5 show that the BRI has a significant positive impact on the EF of both countries with medium-high and low EFD. However, it is evident that the impact of the BRI on countries with low EFD is significantly higher than that on countries with medium-high EFD. Similarly, the results in columns (3) and (4) indicate that the BRI also has a significant positive impact on the EF of countries with both medium-high and low per capita EFS, and the impact on countries with low per capita EFS is much greater than that on countries with medium-high per capita EFS. Furthermore, the

Table 4
Quantile regression results.

	0.2	0.4	0.6	0.8
$ydyl_{it}$	0.341*** (0.051)	0.275*** (0.036)	0.204*** (0.042)	0.076* (0.044)
R^2	0.780	0.800	0.810	0.820

Note: *, **, *** indicate significance at the 10%, 5%, and 1% levels, respectively. Standard errors are in parentheses.

Table 3
Mechanism test results.

Variables	Industrial structure (1)	Technological innovation (2)	Foreign direct investment (3)
$ydyl_{it}$	0.067*** (0.035)	2108.590** (1005.014)	3.349* (2.772)
Constant	0.933* (0.145)	24724.290*** (5765.605)	50.193* (27.258)
Country fixed effect	Yes	Yes	Yes
Time fixed effect	Yes	Yes	Yes
Sample size	1909	1909	1909
R^2	0.857	0.806	0.893

Note: *, **, *** indicate significance at the 10%, 5%, and 1% levels, respectively. Standard errors are in parentheses.

results in columns (5) and (6) show that the BRI has a significant positive impact on the EF of countries with both weak and strong sustainability, and the impact on countries with weak sustainability is greater than that on countries with strong sustainability. This disparity can also be combined with the results of the previous mechanism analysis, which states that the BRI has a greater impact on foreign direct investment and technological innovation in countries with weaker sustainability than in those with stronger sustainability, thereby making the BRI's EF more significant for countries with weaker sustainability.

4.4.5. Robustness test

(1) Parallel trends test

The premise of the DID assumption requires the trends of the treatment group and the control group should be consistent before the policy implementation. Therefore, this paper further investigates the trends of the treatment and control groups using the parallel trends test of the DID model. Since the parallel trends test only needs to examine the trends before and after the policy change, this paper tests the trend changes from 5 years before the proposal of the BRI to 5 years after its proposal. The analysis results are shown in Fig. 13. It can be found that the regressions before 2013 are not significant, indicating that the treatment group and the control group has the same trend before 2013. After 2013, compared to the control group, the EF of the treatment group significantly has kept rising. Therefore, this paper passes the parallel trends test required for the DID.

(2) Placebo test

To examine whether there are other unobservable country-specific ecological characteristic variables that vary over time and influence the estimation results, this paper conducts a placebo test on the main findings by randomly selecting economies from Eurasia sample. Since this paper includes a total of 83 countries and regions, 64 of which are the BRI economies, we first randomly select 64 economies from the 83 countries and regions and designate them as the “pseudo” treatment group of BRI economies, while the remaining economies are designated as non-"Belt and Road” economies. This random sampling process is repeated 500 times for the placebo test, with the results shown in Fig. 14. As can be seen from the figure, the distribution of regression coefficients in the model is concentrated around 0, indicating that the randomly sampled combinations of economies have no impact on the EF. Therefore, it can be concluded that the estimation results are not seriously biased due to omitted variables.

(3) Shortened sample period test

This paper also tests whether the baseline regression results are significant by shortening the sample period. This testing method shortens the selected sample period from 2000 to 2022 to 2007–2018, examining whether the BRI significantly affects the EF changes of Eurasian countries in a short period. The specific results are shown in column (1) of Table 6, indicating that the regression results remain significant after shortening the sample period, with positive coefficients.

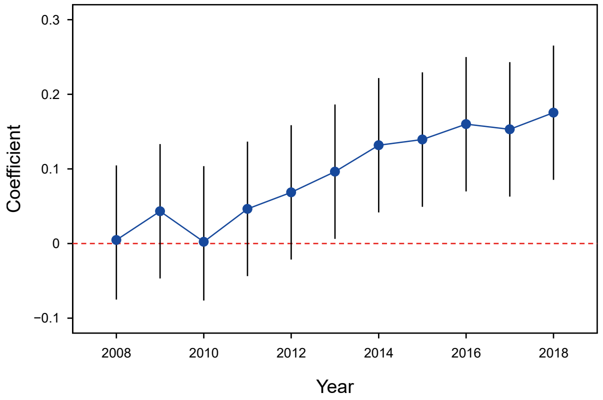


Fig. 13. Parallel trends test.

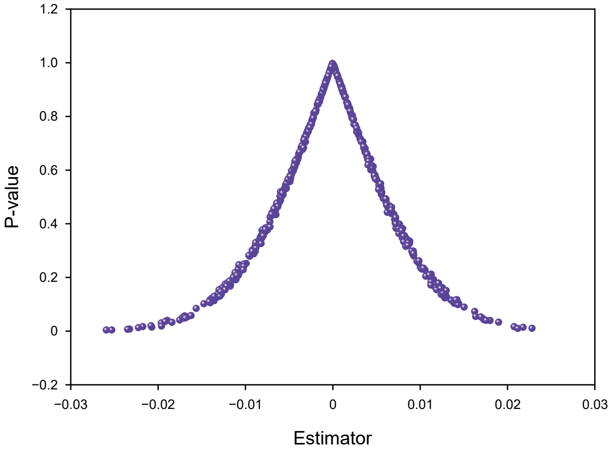


Fig. 14. Placebo test.

(4) Redefinition of the treatment group

In the baseline regression, the treatment group is defined based on whether a country has joined the BRI. However, considering the inconsistent timing of countries joining the BRI, this paper redefines the treatment group by designating countries that had joined the initiative by 2017 as the treatment group and the remaining countries as the control group. After redefining the treatment group, the regression results are shown in column (2) of Table 6. It can be seen that although the coefficient in the baseline

Table 5
Results of heterogeneity analysis.

Variables	EFD		Per capita EFS		Sustainability types	
	Low (1)	Medium-high (2)	Low (3)	Medium-high (4)	Weak (5)	Strong (6)
$ydyl_{it}$	0.156*** (0.017)	0.047* (0.023)	0.188*** (0.020)	0.080*** (0.019)	0.169*** (0.020)	0.117*** (0.022)
α	−7.775*** (1.074)	2.376*** (0.677)	1.605* (0.919)	−9.225*** (1.495)	−5.753*** (1.029)	1.081* (0.879)
Country fixed effect	Yes	Yes	Yes	Yes	Yes	Yes
Time fixed effect	Yes	Yes	Yes	Yes	Yes	Yes
Sample size	1486	423	1041	868	1307	602
R^2	0.928	0.912	0.834	0.946	0.895	0.920

Table 6
Shortened sample period test.

Dependent variable	(1)	(2)	(3)	(4)
$ydyl_{it}$	0.089** (0.027)	0.111** (0.037)	0.161*** (0.038)	0.222*** (0.048)

regression weakens, it remains significant. This suggests the BRI has a more profound promoting effect on the EF of countries have been members for a longer time compared to those have joined more recently, verifying the impact of the BRI on the EF of Eurasian countries from another perspective.

(5) DID model base on propensity score matching

Due to selective bias arising from differences in social and economic development among Eurasian countries, which may lead to biased estimation results, the propensity score matching model can relatively eliminate this bias. Therefore, this study uses control variables as a baseline and adopts a nearest neighbor 1:1 matching of samples. The specific results are shown in column (3) of Table 6, indicating that the BRI indeed has a significant positive correlation with the EF of Eurasian countries, demonstrating the reliability of the conclusions in this paper.

(6) Random policy time test

Considering the BRI has different impacts on different countries at different time points, this paper also conducts a random policy time test by randomly selecting a subset of countries and time points to perform regression analysis on the dependent variable. The results are shown in column (4) of Table 6, and they still validate the previous regression conclusions, namely, that the BRI has a significant positive correlation with the EF of Eurasian countries.

5. Conclusions

This paper first conducts an in-depth analysis of the EFD and per capita EFS across Eurasia. Building on these findings, it employs a three-dimensional ecological footprint model to assess national sustainability levels from 2000 to 2022. Subsequently, a DID approach examines the impact of the Belt and Road Initiative on the ecological footprint of Eurasian countries. Key conclusions are as follows.

(1) Divergent trends in per capita EF: Eurasia's overall per capita EF exhibits an upward trend, yet significant regional disparities exist: Asia shows a lower but rising per capita EF, while Europe demonstrates a higher yet declining footprint (albeit with fluctuations). Fossil energy land and cropland dominate the EF composition in both regions, though their relative contributions differ. Concurrently, per capita ecological carrying capacity displays a stable upward trajectory across Eurasia, with Europe's capacity substantially exceeding Asia's.

(2) Worsening unsustainability driven by EFD: EFD across Eurasia continues to increase, while per capita EFS experiences a slight decline, collectively indicating a falling utilization rate of natural capital flows. This confirms unsustainable development in both Asia and Europe, with conditions deteriorating. Asia's significantly higher EFD relative to Europe further signals greater resource scarcity. Case studies of Ukraine, Denmark, and Syria reveal that factors like conflict, environmental policy implementation, and industrial restructuring drive substantial changes in EFD and per capita EFS.

(3) Sustainability typology and regional contrasts: Classification based on the three-dimensional ecological footprint model groups 83 Eurasian countries into six distinct sustainability types. Asia exhibits weaker overall sustainability, predominantly characterized by LM (Low size-medium depth) and LL (Low size-low depth) types. In contrast, Europe presents a more favorable outlook, dominated by the LM type. Notable shifts occurred: Saudi Arabia showed significant improvement, while Italy experienced marked deterioration.

(4) BRI impact and heterogeneous effects: The BRI exerts a significant positive effect on the EF of Eurasian countries, mediated by industrial structure, technological innovation, and foreign direct investment. Quantile regression indicates this effect is stronger in countries with lower initial EF. Heterogeneity analysis further reveals the BRI's impact is larger on countries with lower EFD, lower per capita EFS, and weaker sustainability types.

(5) Robustness of findings: The reliability of these results is confirmed through multiple robustness checks, including parallel trends tests, placebo tests, shortened sample period tests, redefined treatment groups, PSM-DID, and random policy timing tests.

Based on the above conclusions, this paper proposes targeted suggestions from the two dimensions of the EF and EC:

In terms of reducing the EF: (1) Optimize and upgrade the industrial structure. As analyzed earlier, countries participating in the BRI have varying levels of development and are affected differently by the initiative. Therefore, it is necessary to optimize the industrial structure based on the current situation of each country. Countries with low EF, which are more significantly influenced by the BRI and experience faster growth in the EF, should pay more attention to developing green productivity, improving relevant systems and policy frameworks, allocating resources reasonably, enhancing resource utilization efficiency, and promoting the coordinated development of secondary and tertiary industries. Countries with high EF already have their own industrial advantages and should adhere to conservation, clean, and safe development to achieve sustainability. (2) Increase investment in technological innovation. Governments should enhance incentives for corporate innovation, significantly improve energy utilization efficiency, and tackle green technology challenges. Green development and economic development are inherently aligned, and reducing EF can actually facilitate more rational economic development. (3) Establish a reasonable foreign investor access mechanism. Currently, there are differing views in academia regarding the role of foreign direct investment. There are two mainstream hypotheses: the “pollution haven” hypothesis, where foreign investment is positively correlated with domestic EF, and the “pollution halo” hypothesis, where foreign investment brings technology transfer and the dissemination of environmental protection concepts, contributing to improving local environmental protection levels. Regardless of which hypothesis holds, governments introducing stricter environmental policies and raising the standards for foreign investment entry can effectively reduce EF.

In terms of enhancing the EC: (1) Reasonably increase the development of agricultural and forestry technologies based on local conditions. Cropland accounts for the largest proportion of land use in Eurasia and contributes the most to EC. Moreover, agricultural technology in Asian countries is generally low.

Therefore, it is necessary to improve soil fertility, enhance crop genetics, cultivate new varieties, and increase the productivity and stability of agricultural ecosystems to provide more material support for ecosystems. European countries should continue to deepen the development of forestland. (2) Asia should strengthen desertification control efforts. Asia has diverse climatic conditions and extensive desertification areas, with many regions lacking freshwater resources. It is necessary to enhance vegetation restoration, increase forest cover, improve water conservation capabilities, and rationally utilize water resources through water-saving measures and water recycling. (3) Eurasian countries should also improve environmental protection regulations. Europe currently has a much higher per capita ecological carrying capacity than Asia and should continue to refine relevant environmental protection regulations to prevent ecological degradation. While continuously improving the ecological environment, Asian regions should also strictly prohibit actions such as excessive emissions, reduce pollutant discharges, and protect the health of ecosystems.

In this study, when assessing the impact of the BRI on the EF of the Eurasian continent, the main basis was existing statistical data and model analysis, which may have limitations in terms of data timeliness and completeness. Future research can combine field investigations and longer time series data to more accurately evaluate the policy effects. Moreover, although this study analyzed various influencing factors, it did not comprehensively cover all potential variables, such as the policy implementation intensity and international cooperation mechanisms, which have complex impacts on the EF. Future research can further delve into these aspects to provide more comprehensive guidance for the sustainable development of the BRI.

CRediT authorship contribution statement

Nan Yu: Conceptualization, Methodology, Writing – original draft. **Tianming Shao:** Resources, Investigation, Data curation, Writing – review & editing. **Renjin Sun:** Writing – review & editing, Funding acquisition, Supervision. **Chunming Xu:** Visualization, Funding acquisition, Writing – review & editing, 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.

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