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The Impact of Urban Construction Land Expansion on Carbon Emissions from the Perspective of the Yangtze River Delta Integration, China

Xing Niu [1], Fenghua Liao [2], Zixuan Mi [1] and Guancen Wu [3,*]

[1] School of Social and Public Administration, East China University of Science and Technology, Shanghai 200237, China; niuxing@ecust.edu.cn (X.N.); y30221489@mail.ecust.edu.cn (Z.M.)
[2] Shanghai Huangpu District Planning and Natural Resources Bureau, Shanghai 200001, China; 15162125916@163.com
[3] School of Management, Shanghai University, Shanghai 200444, China
* Correspondence: wuguancen@shu.edu.cn

Abstract: Regional integration plays a pivotal role in the socio-economic advancement of various global regions and is closely linked with the expansion of construction land. This expansion is a major contributor to urban carbon emissions. Utilizing a geographical regression discontinuity design (GRDD), this paper estimates the impact of urban construction land expansion on carbon emissions and explores the underlying mechanisms within the regional integration process of the Yangtze River Delta (YRD), China. The findings reveal that urban construction land expansion significantly influences carbon emissions, displaying an inverted "U"-shaped pattern. Furthermore, this expansion affects carbon emissions through the transformation of industrial structures, shifts in consumption patterns, and enhancements in scientific and technological investments. Our findings span the performance of the Yangtze River Delta from its early development stages to a relatively mature phase. This paper also partially reveals how the Yangtze River Delta, with both megacities and large- to medium-sized cities, manages urban construction land expansion during the integration process and strives for low-carbon emissions reduction. These results can provide green growth recommendations that balance socio-economic development, low-carbon emissions, and social equity not only for other urban agglomerations in China but also for similar regions in other developing countries by altering construction land utilization patterns.

Keywords: urban construction land expansion; carbon emission; geographical regression discontinuity design; influencing mechanism; Yangtze River Delta integration

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1. Introduction

Regional integration has become a significant driver of economic growth for developing countries and regions by promoting trade facilitation, optimizing resource allocation, expanding markets, and sharing welfare [1–3]. However, regional integration brings about various changes in different elements and resources, which profoundly impact the carbon emissions of the region. In particular, the land use changes accompanying regional integration not only affect soil carbon storage but also influence human activity-related carbon emissions by altering the connections between socio-economic and natural systems [4–6]. Construction land is the most important type of land use for various socio-economic activities such as residential living, construction, transportation, and industrial production. It fundamentally supports regional economic development and operations, and it is also the area with the highest concentration of carbon emission activities [7].

The development of regional socio-economics and urbanization has accelerated the expansion of construction land globally, with some areas even experiencing unregulated expansion [8]. The expansion of construction land increases direct carbon emissions and

occupies a large amount of vegetation-covered ecological land, weakening the surface carbon sink capacity and carbon sequestration [9]. Additionally, due to the different use purposes, usage methods, and intensities of various types of construction land, the corresponding energy consumption demands also vary [10]. There are also differences in carbon emissions from construction land in different regions and cities of varying scales. [11,12].

The Yangtze River Delta is one of the earliest and most mature regions of regional integration in China. Like other countries and regions, the process of regional integration inevitably accompanies the expansion of construction land. Local governments often face the dilemma of being unwilling to sacrifice economic growth to promote environmental protection [13]. Even in some land-abundant areas of the United States, low-density expansion leads to inefficient land use, particularly increasing transportation-related carbon emissions [14]. The Yangtze River Delta's integrated development process also experiences long-term growth in construction land patterns and reliance on high-carbon economic growth models. It faces issues such as insufficient stock development of construction land, uncontrolled urban sprawl, high resource and energy consumption, and significant ecological environment differences between regions.

Although the Yangtze River Delta's unit GDP carbon dioxide emissions and energy consumption are lower than the national average, overall carbon emissions are on an increasing trend. As climate change and carbon emissions issues gain global attention, China is increasingly pursuing the development concepts of innovation, coordination, greenness, openness, and sharing. At the 75th session of the United Nations General Assembly, China officially announced its "dual carbon goals", which are reaching peak carbon emissions by 2030 and achieving carbon neutrality by 2060.

As the most economically integrated and developed region in China, the Yangtze River Delta has become a pioneer in promoting balanced economic growth and green transformation and a key region for achieving China's dual carbon goals. Shanghai, the core city in the Yangtze River Delta, has explicitly proposed a timetable to achieve peak carbon emissions by 2025. Jiangsu Province and some cities in Zhejiang Province in the Yangtze River Delta have also set targets for key industries or sectors to achieve peak carbon emissions to varying degrees. However, the impact of urban construction land expansion on carbon emissions is complex. They are not simply influenced by a linear relationship but are to be studied specifically from the perspective of process development [15]. As the target year for reaching peak carbon emissions approaches, how to improve the efficiency of construction land use, advance carbon reduction, and narrow regional disparities during the process of regional integration has become a key issue for the sustainable development of the Yangtze River Delta. This also makes it a suitable and representative area for research.

This paper uses the Yangtze River Delta as a case study to examine the impact of urban construction land expansion on carbon emissions during the regional integration process and conducts an in-depth analysis of the underlying mechanism. This topic is a focal point of interest not only for academia but also for relevant local government departments. It is hoped that the findings of this research can provide empirical evidence for regional sustainable development and assist other similar regions worldwide in understanding and addressing the environmental challenges posed by urban construction land expansion.

2. Literature Review

Many scholars have analyzed and studied the relationship between urban construction land expansion and carbon emissions using different research methods and data.

In terms of the relationship between the total amount of construction land and carbon emissions, most scholars agree that construction land is a major source of carbon emissions. The expansion of construction land increases the consumption of materials and energy, thereby driving the growth of carbon emissions [16]. Feng et al. (2020) studied the relationship between urban construction land use changes and carbon emissions, finding that the increase in construction land and the reduction in vegetation cover led to a significant

decline in carbon stocks [17]. Niu et al. (2023) used the central Yunnan urban agglomeration as the study area, based on construction land data from 2011 to 2020, employed a multiple linear regression model, and found a significant positive correlation between carbon emissions and the level of construction land in the central Yunnan urban agglomeration [18]. Other scholars have also examined the impact of specific types of construction land on CO_2 emissions [19–22].

As research has deepened, some scholars have noted the nonlinear impact of construction land on carbon emissions. Using panel data from 278 prefecture-level cities in China from 2000 to 2019, Peng et al. (2022) found that the increases in new construction land and industrial land are significant sources of carbon dioxide emissions. The impact of urban construction land changes on urban carbon emissions exhibits an inverted U-shaped trend, first increasing and then decreasing [23]. Deng et al. (2015) classified 30 Chinese provinces into 8 regions. Using the Kaya identity and the Logarithmic Mean Divisia Index (LMDI) method, the analysis found that the impact of construction land expansion on carbon emissions varies across provinces. The impact of construction land expansion on carbon emissions shows a declining trend nationwide [11].

Scholars have thus conducted spatial heterogeneity analyses of the impact of construction land on carbon emissions from different perspectives. Li et al. (2023) estimated the carbon emission intensity of construction land (CEICL) for 285 Chinese cities from 2008 to 2019. Using a spatial panel quantile regression model, they found that CEICL decreases with the increase in city size, although the regional differences are gradually diminishing [24]. Yang et al. (2022) utilized the LMDI model to explore the spatial variability of the CO_2 emission potential from urban construction land in 30 Chinese provinces from 2000 to 2018, analyzing the driving effects of economic, demographic, energy intensity, and energy emissions factors [25]. Wang et al. (2022) studied 1042 counties in the Yangtze River Economic Belt in China, constructing a dataset that includes factors such as the scale of construction land, GDP, the proportion of the secondary industry's output to GDP, population, and fixed asset investment. Using the geographically weighted regression (GWR) method, they indicated that the scale of construction land has the most significant impact, and that its influence on carbon emissions exhibits notable spatial heterogeneity [26].

With increasing attention on carbon emissions and land use patterns and quality in China, Li et al. (2022) used land cover data from 137 county-level administrative units in Shandong Province from 2000 to 2020 to estimate the carbon emissions and carbon sequestration of different land types. They found that land use intensity and technological innovation efficiency restrained carbon emissions, and the relationship between net carbon emissions and construction land evolved from an expansive negative decoupling type to a strong negative decoupling type [9]. Wang et al. (2023) explored the mechanisms by which land use methods affect carbon emissions and found that the relationship between land use and carbon emissions in the high-efficiency eco-economic zone of the Yellow River Delta in China shifted from an expansive negative decoupling to a weak decoupling [27]. Li et al. (2019) examined the decoupling effect of construction land on carbon emissions from the perspective of Shanghai, finding that between 1999 and 2015, the annual growth in carbon emissions from construction land and the growth in construction land area exhibited varying degrees of decoupling, driven primarily by economic output from land and energy intensity [28]. Lv et al. (2023) used statistical data from the Urban Agglomeration in the Middle Reaches of the Yangtze River (UAMRYR) from 2006 to 2020 and concluded that the capital-intensive and technology-intensive use of urban construction land significantly improves carbon emission efficiency (CEE), while labor and energy-intensive use suppresses CEE [29]. Tang et al. (2021) argued that low-level industrial development and land use management promote increased carbon emissions during the extensive land use stage, whereas high-quality industrial development and land use optimization reduce carbon emissions during the intensive land use stage [30]. Stone (2008) used data from 45 major U.S. cities and found that sprawling cities generate more air pollutants than compact cities [31]. Makido et al. (2012) measured the compactness of land

use in 15 Japanese cities and found that compact cities have lower carbon emissions than sprawling cities [32].

It can be seen that in studies on the relationship between construction land area and carbon emissions, most researchers include factors such as economic development level, industrial structure, energy intensity, energy consumption structure, population size and composition, fixed asset investment, urbanization level, technological progress, etc., as influencing or control variables. They employ the STIRPAT model, the Kaya identity equation, and the LMDI method, using panel data, or adding spatial analysis to analyze regional differences. These studies are conducted at national, provincial, urban agglomeration, or specific administrative district levels. Although these methods have their respective advantages, they also come with specific requirements and applicability. There are still some limitations in their application to addressing the impact of construction land use on carbon emissions in the process of regional integration. The traditional STIRPAT model, the Kaya identity equation, and the LMDI method are prone to overlooking certain new variables and relying on simplistic linear relationships. Even with panel data regression incorporating spatial elements such as dummy variables, there may still be issues with unmeasured variables or difficulties in completely isolating the effects of regional integration policies, particularly when certain influencing factors exhibit ambiguous changes before and after policy implementation. Spatial econometric analyses, including spatial metrics, tend to focus more on regional disparities and the correlation between variables, requiring further refinement in analytical design for causal inference interpretation. However, incorporating the perspective of Yangtze River Delta integration into the analysis poses a challenge.

Geographic regression discontinuity design (GRDD) is an extended form of regression discontinuity design (RDD) [33], initially proposed by Hahn et al. (2001) [34], and further developed with a more robust theoretical foundation by Imbens and Lemieux (2008) [35] as well as Keele and Titiunik (2015) [36]. This approach leverages discontinuities in geographical boundaries or spatial distributions to estimate causal effects. These boundaries are often the result of natural or policy-based delineations and are unrelated to individual characteristics. On either side of the geographical boundaries, apart from the treatment variable, other factors that may influence the outcome variable are often relatively stable or similar. This helps to reduce the impact of omitted variables. Such a design makes GRDD widely applicable in assessing the spatial effects of policies and interventions.

Keele, Titiunik, and Zubizarreta (2015) [37] utilized Zubizarreta's (2012) [38] matching method in GRDD to estimate the impact of a voting initiative in Milwaukee, Wisconsin, on voter turnout. MacDonald et al. (2016) employed GRDD to explore the effects of cross-border expansion of public services such as police patrols, firefighting, or emergency medical services, and even the impacts of new housing developments or land use rezoning [39]. Alejo et al. (2021) used GRDD to investigate the spatial effects of ITs (Indigenous Territories) and PAs (Protected Areas) boundaries on carbon storage [40]. Rischard et al. (2021) utilized GRDD to simulate spatial structures and explore the impact of school districts on housing prices in New York City [41]. Keele and Titiunik (2015) applied the GRDD to re-examine the effects of political advertisements on voter turnout during a presidential campaign, leveraging exogenous variations in the volume of presidential ads created by media market boundaries [36]. D'Arcangelo and Percoco (2015) employed the GRDD method, controlling for dynamic differences in geographic variables, to overcome some limitations of simple discontinuity designs, and studied the impact of road pricing schemes (Ecopass) on the housing market from the perspective of rent changes [42]. Chen et al. (2013) used the "Qinling–Huaihe River" centralized heating boundary as a geographic discontinuity line to study the impact of centralized heating on air quality [43]. To address endogeneity issues in existing research, Liu et al. (2019) used the framework of GRDD to infer the impact of the "county-to-district" policy on regional economic development and discussed its impact mechanism in detail [44].

In this paper, the GRDD method is employed to estimate the impact of construction land expansion on carbon emissions as well as to test the inverted U shape. Some

mediating variables are selected to analyze the impact mechanism of land expansion on carbon emissions. The contribution of this paper has two main aspects. First, compared with the existing studies, this study adopts the method of GRDD to explore the impact of land expansion on carbon emissions in the YRD region, which emphasizes the perspective of regional integrated development. Second, this study mainly focuses on the factors of environmental pressure related to land use in the process of regional integration and development, analyzing the specific influence mechanism of urban construction land expansion on carbon emissions from three dimensions of industrial transformation, consumption pattern, and technological investment.

The remainder of this paper is structured as follows: Section 3 provides a theoretical analysis of changes in construction land and their impact on carbon emissions. Section 4 covers the materials and methods, including the rationale for selecting the study area and the detailed design of the methodology. Section 5 reports the research results, including the results of the geographical regression discontinuity design, robustness analysis, the inverted U-shaped nonlinear relationship, and the mechanism analysis. Section 6 discusses the research results in comparison with existing studies and offers relevant recommendations. Section 7 provides a summary of the entire paper and highlights the limitations of the study.

3. Theoretical Analysis

The process of regional integration promotes close economic cooperation and synergistic development among regions, making economic activities within the region more dynamic. This increase in economic activities typically requires more construction land to support industrial development, infrastructure construction, and the demand for residential and commercial land. However, when regional integration reaches a certain level, accompanied by a reduction in available construction land space, both the extent of the expansion in construction land area and land use patterns within the region will undergo alterations.

Through inter-regional cooperation, the agglomeration effects brought about by the expansion of urban construction land directly impact the industrial structure, primarily manifested in the transition from primary industries to secondary and tertiary industries (non-agricultural industrial), as well as upgrading from secondary to tertiary industries. The efficient allocation and optimized utilization of construction land will gradually phase out enterprises characterized by high pollution, high energy consumption, high emissions, and low productivity, driving industries towards higher value-added and higher technological content. In the context of regional integration, the expansion of construction land can improve infrastructure construction levels, connect them, and create new employment opportunities. Thereby, it enhances the convenience of life and improves levels of consumption. Combined with the transformation of the social economy, it also influences residents' consumption structure and preferences. At the deeper development stage of regional integration, the expansion of construction land favors the construction of new production bases, research and development centers, science parks, and supporting facilities. This requires increased government investment in technology, providing financial support or tax incentives to attract a large number of scientific talents and enterprises, thus enhancing innovation capacity.

During the process of industrial structural transformation, the increase in secondary and tertiary industries will lead to an increase in carbon emissions, especially in high carbon emission and high energy consumption sectors within the secondary industry [45]. Inter-regional industrial transfer, the formation of industrial chains, and the improvement in industrial specialization intensify the elimination of backward production capacity and enterprises with weaker competitive strength, driving the optimization and upgrading of industrial structures. This relatively reduces the proportion of high carbon emission industries while increasing the proportion of service industries, high-tech industries, and clean energy industries, which helps to lower overall carbon emission levels [46]. The improvement in residents' consumption levels and changes in consumption structure will increase the demand for energy and high carbon footprint products and services, which in turn

increases carbon emissions. However, green and low-carbon consumption habits can partially mitigate this impact, facilitating the accelerated relocation of high-energy-consuming enterprises and thereby reducing the carbon emissions of cities within regional integration. In the initial stages of technological investment, it may not be "green-oriented" and may focus more on the efficiency of traditional production technologies. The research and application of new technologies require substantial energy and raw materials, which may lead to an increase in carbon emissions during the corresponding period, a phenomenon known as the rebound effect [47]. However, as technological investment increases, especially in the areas of green technology, energy-saving technology development, and the application of low-carbon technologies, it can reduce energy consumption and carbon emissions per unit of output, improving energy efficiency [48]. Monitoring and controlling carbon pollution will also become more efficient and effective [49]. In the context of regional integration, expanding the scope of cooperation among innovation entities can provide new momentum for the spillover of innovative elements and "green barriers" [50], thereby reducing carbon emissions on a broader scale.

Therefore, this study suggests that regional integration processes generally lead to increased expansion of construction land and carbon emissions. The use of construction land also promotes increased carbon emissions. However, as regional integration deepens and there is a greater emphasis on low-carbon, intensive land use, and reutilization of existing land, this trend may change and improve. It may even lead to the occurrence of carbon peaking or decoupling. The expansion of construction land mainly affects carbon emissions through industrial structure transformation, residential consumption, and technological investment. Since the mechanisms of these effects vary at different stages of regional integration, relevant policies need to comprehensively consider these factors to achieve a win–win situation for economic development and low-carbon emission reduction [51].

In line with research objectives, we follow the procedure outlined below (Figure 1). Based on theoretical analysis, we first identify the sample cities for our study, including both the treatment and control groups within and around the Yangtze River Delta integration region, thus clearly defining the geographical boundaries. We then compare carbon emissions and changes in construction land between the treatment and control groups. By incorporating control variables, we explore the impact of construction land in the treatment group on construction land changes. Subsequently, we progressively analyze and verify the impact of construction land in the treatment group on the mediating variables, as well as the influence of these mediating variables on carbon emissions.

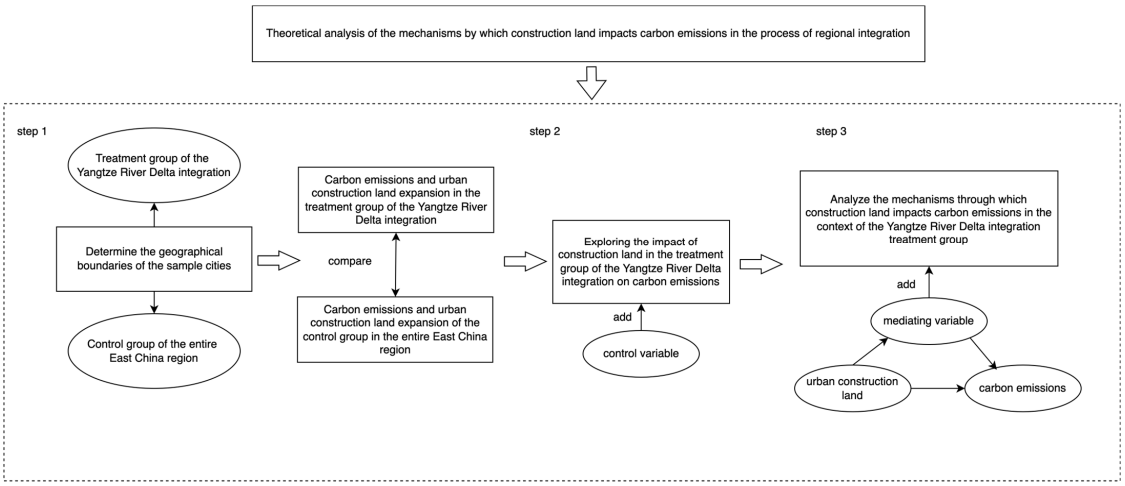


Figure 1. Analysis procedure diagram.

4. Materials and Methods

4.1. Study Area

As early as 1982, China proposed the establishment of the Yangtze River Delta Economic Zone with Shanghai as its center. However, substantive regional cooperation among the cities in the Yangtze River Delta only began with the establishment of the "Yangtze River Delta 15 Cities Economic Coordination Joint Conference System" in 1992. In 1997, this system was upgraded to the "Yangtze River Delta Cities Economic Coordination Association." In October 2010, the State Council officially approved the "Regional Plan for the Yangtze River Delta Region," marking the beginning of national-level attention to the integration of the Yangtze River Delta region. The plan emphasized strengthening cooperation among the core areas of Shanghai City, Jiangsu Province, and Zhejiang Province, as well as the broader Yangtze River Delta area, including Anhui Province. That same year, the Yangtze River Delta Economic Coordination Association formally expanded the core urban agglomeration to 22 cities, specifically including the municipality of Shanghai; Nanjing, Suzhou, Wuxi, Changzhou, Nantong, Zhenjiang, Taizhou, Yancheng, and Huai'an in Jiangsu Province; Hangzhou, Jiaxing, Huzhou, Ningbo, Shaoxing, Zhoushan, Yangzhou, Taizhou, Jinhua, and Quzhou in Zhejiang Province; and Hefei and Ma'anshan in Anhui Province. This enlargement transcended natural geographical boundaries. According to the classification of Chinese city sizes, these regions include one megacity, several super-large cities, large cities, and medium-sized cities, making the analysis more universally applicable.

Subsequently, in 2018, the Chinese government elevated the integration of the Yangtze River Delta region to a national strategy, providing increased support in terms of policies, funding, and projects. The requirements for low-carbon and green development have also evolved. The development of the Yangtze River Delta must now also coordinate with other major national strategies such as the Belt and Road Initiative and the Beijing–Tianjin–Hebei urban agglomeration development. Moreover, an increasing number of cities have joined the Yangtze River Delta cooperative body, achieving comprehensive coverage of the three provinces and one municipality (Shanghai, Jiangsu, Zhejiang, and Anhui) by 2019. Additionally, the impact of the COVID-19 pandemic on China's socio-economic development over the past three years remains significant and uncertain.

Therefore, to maintain the uniformity of sample data and account for the development process of the Yangtze River Delta integration from its early stages to recent times, this study uses the 22 administrative districts included in the 2010 Economic Coordination Association as the geographical boundaries of the Yangtze River Delta region. The study period is set from 2000 to 2017. This period not only provides reliable and stable data but also represents a timeframe where the impact of construction land on carbon emissions is more representative, reflecting the objectives of this research. To eliminate interference from other major urban agglomerations and minimize estimation bias caused by the heterogeneity of various Chinese cities, this study uses other cities in the adjacent East China region (77 cities in total, including Shandong province, Jiangsu province, Anhui province, Jiangxi province, Fujian province, Zhejiang province, and Shanghai) as the control group. Figure 2 shows the location of the study sample cities.

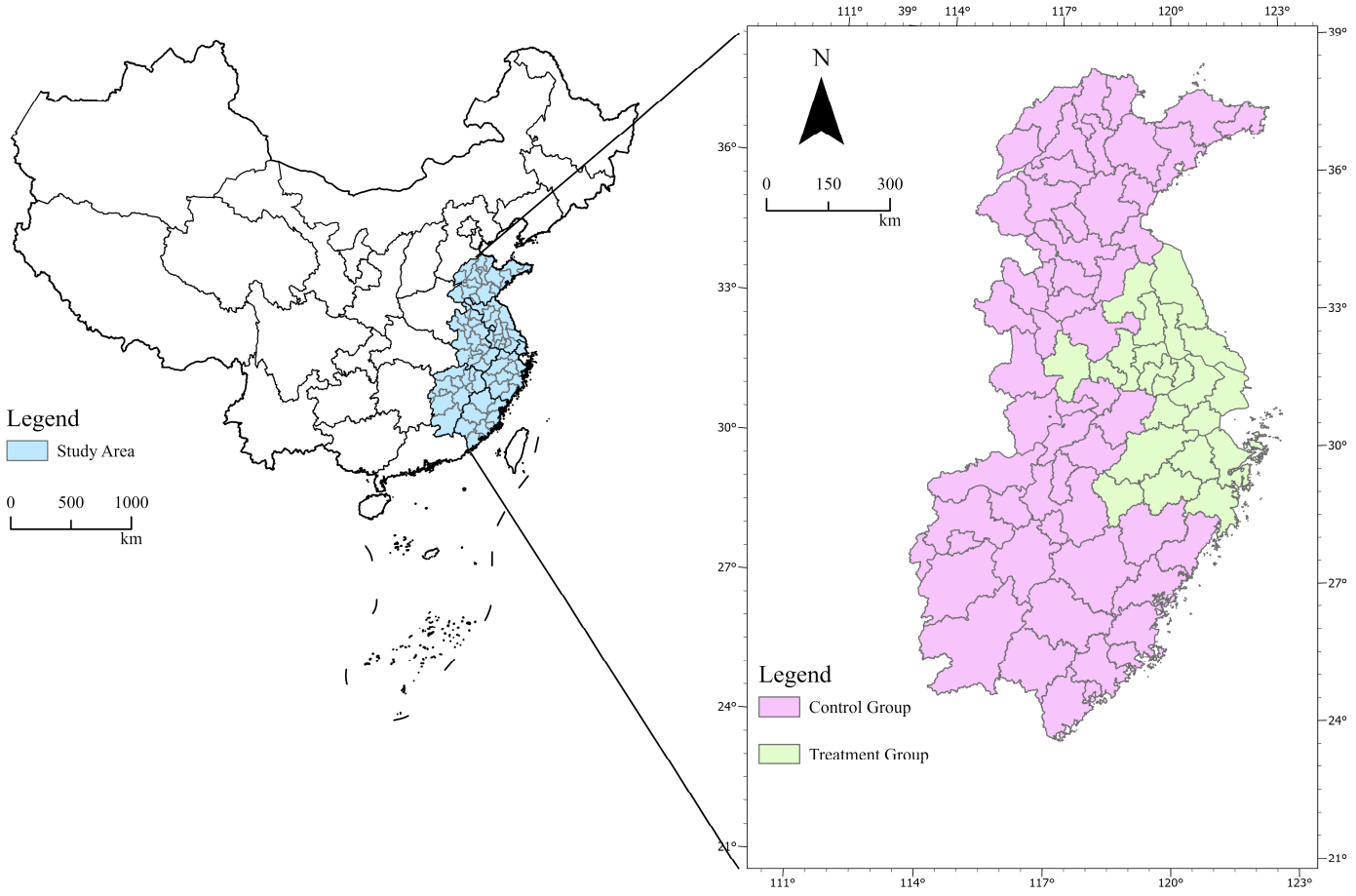


Figure 2. Location of sample cities.

4.2. Methods

4.2.1. Geographic Regression Discontinuity Design (GRDD)

This study employs GRDD to analyze the impact of construction land on carbon emissions during the integration of the Yangtze River Delta. The design adopts the boundary of the Yangtze River Delta as the geographical cutoff point. The driving variable, drawing on the approach of Ito et al. (2020) [52], is the shortest distance from the center of the sample city to the Yangtze River Delta boundary (measured in units of 100 km). This design ensures the characteristics of a randomized natural experiment, effectively identifying the causal relationship between urban construction land expansion and carbon emissions. The study can further control for provincial administrative divisions and year-fixed effects, respectively serving as spatial and time-fixed effects, thereby reducing estimation bias. The econometric model equation is designed as follows:

$$CE_{it} = \alpha_0 + \alpha_1 N_{it} + \alpha_2 f(D_i) + \alpha X_{it} + \rho_i + \delta_t + \varepsilon_{it} \quad (1)$$

$$UCL_{it} = \beta_0 + \beta_1 N_{it} + \beta_2 f(D_i) + \beta X_{it} + \rho_i + \delta_t + \varepsilon_{it} \quad (2)$$

$$CE_{it} = \gamma_0 + \gamma_1 UCL_{it} + \gamma_2 f(D_i) + \gamma X_{it} + \rho_i + \delta_t + \varepsilon_{it} \quad (3)$$

where i is the number of research cities, t represents time, CE_{it} represents urban carbon emissions, and UCL_{it} represents the area of urban construction land. D_i is the shortest distance from the city center to the boundary of the Yangtze River Delta region, which is positive within the Yangtze River Delta region and negative outside the Yangtze River Delta region, and N_{it} is the processing variable. When $D_i > 0$, $N_{it} = 1$, the urban sample is the treatment group. When $D_i < 0$, $N_{it} = 0$, the urban sample is the control group. X_{it} is the control variables, ρ_i is the spatial effect, δ_t is the time effect, ε_{it} represents the error term,

and γ_1 is the main coefficient of interest in this paper, representing the impact of urban construction land expansion on carbon emissions. The driving variable is the shortest distance (in 100 km) from the sample city center point to the YRD boundary, which is estimated with ArcGIS and the methodology in reference [52].

4.2.2. Control Variable Selection

Drawing on existing related research [24,26,53–56], this study controls for relevant influencing factors at the city level as much as possible. Specifically, (1) per capita gross domestic product (PGDP) is used to represent the level of economic development; (2) population urbanization rate (PU) is used to represent the level of urbanization; (3) population density (PD) is used to represent the degree of population concentration; (4)public fiscal expenditure (PFE) is used to represent the government's investment in urban construction; (5) intensity of foreign direct investment (FDI) is the ratio of foreign investment to GDP, which is used to measure the degree of openness; (6) energy utilization efficiency (NUE) is the GDP generated per unit of energy consumption; (7) road network density (RD) is used to represent transportation development; and (8) urban greening rate (UGR) is used to represent the carbon sequestration capacity of urban ecological land.

4.3. Data Source and Descriptive Statistics

The concept of "carbon emissions" in this study refers to CO_2 emissions, which is also the main dependent variable. The data were gathered from the Carbon Emission Accounts and Datasets (CEADs, https://ceads.net/) [57]. The CO_2 emissions inventory of CEADs is compiled according to the IPCC's (Intergovernmental Panel on Climate Change) territorial emission accounting approach. To avoid underestimation, the study adopts a bottom-up approach where carbon emissions data for prefecture-level cities are synthesized from county-level data across various regions. This approach considers both fossil fuel-related emissions from 47 socioeconomic sectors and 17 types of fossil fuels, as well as process-related emissions from cement production. Although it cannot precisely and comprehensively measure a city's carbon emissions across all aspects, such as building operations and transportation, it effectively captures carbon emissions from human economic activities related to construction land production and economic operations within the city's territory to a certain extent. The core independent variable of this study is the data on urban construction land, specifically the area of construction land at the end of the current year. The data are sourced from the "China Urban Construction Statistical Yearbook" and the statistical yearbooks of Jiangsu Province, Anhui Province, Zhejiang Province, and Shanghai. All control variable data are sourced from the "China City Statistical Yearbook" and the statistical yearbooks and bulletins of various provinces and cities.

The symbols, definitions, calculation methods, and descriptive statistics for each variable are presented in Table 1. It can be observed that among the sample cities, the standard deviation of public budget expenditure (PFE) is the highest, and there are also significant regional differences in population density (PD). The standard deviation of construction land area (UCL) is greater than that of carbon emissions (CEs). The largest construction land area is 3088 square kilometers, while the smallest is 23.73 square kilometers. Although there is a general increasing trend in construction land area across regions, there has been a noticeable decline in the growth rate in the Yangtze River Delta, particularly in Shanghai, since 2015, with the growth rate nearly reaching zero by 2017. The minimum carbon emissions recorded are 5.624 million tons, and the maximum is 230.712 million tons. The differences in urban green coverage rates (UGR) and GDP per unit of energy consumption (NUE) are relatively minor. Despite the potential influence of varying units on these indicators, the disparities also highlight the distinct characteristics of each city, as well as their differing development priorities and strategies. This suggests that the impact and effectiveness of construction land on carbon emissions vary, necessitating further in-depth investigation.

Table 1. Descriptive statistics of variables.

Variables	Symbol	Measures	Unit	Mean	Standard Deviation	Minimum	Maximum	N
CO_2 emissions	CE	CEADs	mt	35.628	28.770	5.624	230.712	616
Urban construction land area	UCL	China Urban Construction Statistical Yearbook	km^2	183.721	347.018	23.73	3088	616
GDP per capita	PGDP	GDP/population	10^4 yuan/people	7.210	3.732	0.964	29.335	616
Population urbanization rate	PU	Urban population/total population	%	63.480	11.268	36.77	88.86	616
Population density	PD	Total population/urban area	Peoples/km^2	936.779	533.650	142.410	3651.170	616
Public fiscal expenditure	PFE	Annual general public budgeting expenditure	10^8 yuan	431.019	630.453	57.322	7547.621	616
Intensity of Foreign direct investment	FDI	Foreign direct investment/GDP	10^4 dollars/10^4 yuan	0.638	2.516	0.0003	46.155	616
Energy utilization efficiency	NUE	GDP/total energy consumption	10^4 yuan/t	2.115	1.681	0.431	12.195	616
Road density	RD	Road area/urban area	%	0.354	0.421	0.009	3.204	616
Urban green coverage rate	UGR	Green space area/urban area	%	42.533	4.693	21.84	77.78	616

5. Results

5.1. Geographic Regression Discontinuity Results

Before estimating geographic regression discontinuity, it is essential to examine whether there are significant changes in the core variables of the Yangtze River Delta region boundary. Figure 3 illustrates the discontinuous variations in carbon emissions and construction land area inside and outside the boundary of the Yangtze River Delta region during the sample period. The horizontal axis represents the driving variable, namely the shortest distance from the city center of the sample cities to the boundary of the Yangtze River Delta. The vertical axes represent carbon emissions and construction land area, respectively. The left side of the boundary (dark blue dots) and the right side (red dots) represent cities in the outer and inner regions of the Yangtze River Delta, respectively. The light green curve on the left represents the overall trend of carbon emissions and construction land area for cities outside the Yangtze River Delta boundary, while the orange curve on the right represents the overall trend of carbon emissions and construction land area for cities within the Yangtze River Delta boundary. At the discontinuity points, both urban carbon emissions and construction land area show noticeable increasing trends, indicating a preliminary indication of the potential promoting effect of urban construction land expansion on carbon emissions. Evidence from geographic discontinuity provides initial support for the existence of causality between variables, making geographic regression discontinuity design an appropriate estimation method.

Table 2 presents the estimation results of the impact of urban construction land expansion on carbon emissions. Panels A and B show the estimation results of Equations (1) and (2), respectively, while Panel C displays the results of Equation (3). Model (1) employs ordinary least squares regression, while models (2), (3), and (4) are based on geographic regression discontinuity. The estimation results of Equations (1) and (2) indicate that, irrespective of the inclusion of control variables or the control for time or spatial fixed effects at the province level, the carbon emissions and urban construction land area of the treatment group are significantly higher than those of the control group at a 1% significance level. This finding confirms a stronger positive correlation between the urban construction land area and carbon emissions within the Yangtze River Delta integration area. Additionally, the estimation results of Panel C demonstrate that urban construction land expansion still significantly promotes urban carbon emissions at a 1% significance level. Model (4), incorporating both control variables and fixed effects, indicates that for every 1% increase in the urban construction land area, urban carbon emissions will increase by 0.047%.

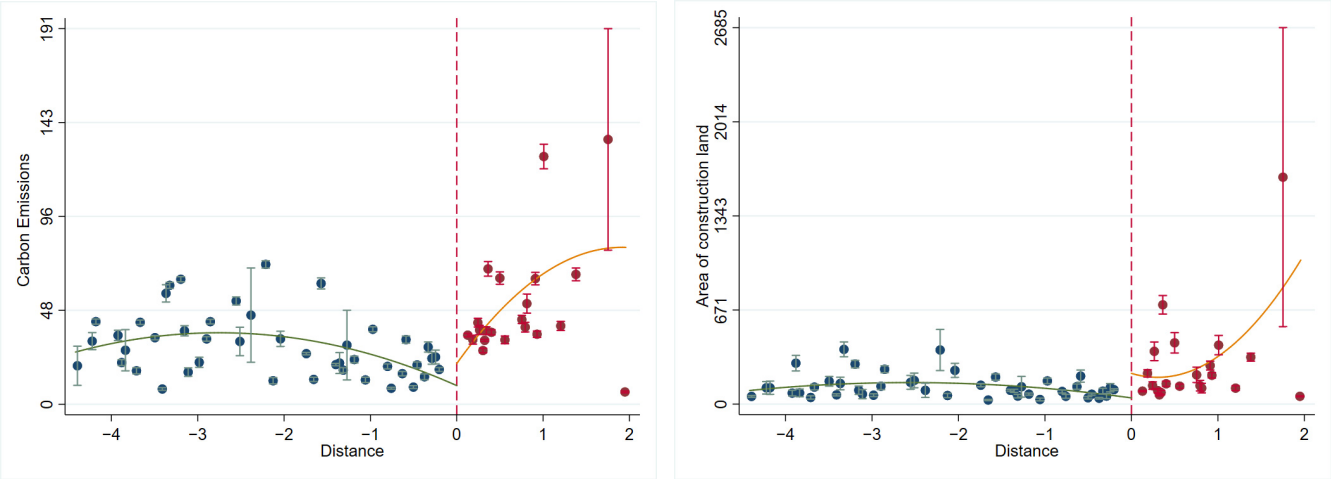


Figure 3. Discontinuity of urban carbon emissions and urban construction land area.

Table 2. Impact of urban construction land expansion on carbon emissions.

	(1)	(2)	(3)	(4)
Panel A:		CE		
N_{it}	9.397 ***	31.545 ***	15.461 ***	13.113 ***
	(1.520)	(3.473)	(2.131)	(2.092)
R^2	0.767	0.170	0.751	0.770
Panel B:		UCL		
N_{it}	33.494 ***	188.780 ***	35.478 ***	35.363 ***
	(11.861)	(43.909)	(12.866)	(12.874)
R^2	0.955	0.088	0.953	0.955
Panel C:		CE		
UCL	0.047 ***	0.067 ***	0.055 ***	0.047 ***
	(0.005)	(0.002)	(0.005)	(0.005)
PGDP	1.987 ***		1.798 ***	1.977 ***
	(0.173)		(0.170)	(0.172)
PU	−0.341 ***		−0.371 ***	−0.359 ***
	(0.040)		(0.041)	(0.041)
PD	−0.002 *		−0.002 **	−0.003 **
	(0.001)		(0.001)	(0.001)
PFE	0.011 ***		0.006 **	0.011 ***
	(0.003)		(0.003)	(0.003)
FDI	−0.304		−0.225	−0.341
	(0.226)		(0.223)	(0.225)
NUE	−0.782 **		−1.401 ***	−1.169 ***
	(0.337)		(0.366)	(0.364)
RD	10.642 ***		11.115 ***	11.190 ***
	(2.224)		(2.257)	(2.222)
UGR	−0.560 ***		−0.605 ***	−0.533 ***
	(0.121)		(0.122)	(0.121)
_cons	48.518 ***	24.092 ***	51.657 ***	50.288 ***
	(5.512)	(0.942)	(5.494)	(5.521)
R^2	0.783	0.680	0.775	0.784
N	616	616	616	616
Time-fixed effect	Y	N	N	Y
Spatial fixed effect	Y	N	N	Y

Note: *, **, and *** represent coefficients that are significant at the 10%, 5%, and 1% levels, respectively. standard error in parentheses.

The performance and coefficients of the control variables largely align with expectations and previous research findings. The regression coefficient for per capita regional GDP (PGDP) is significantly positive, indicating that the intensification of economic interactions and the improvement in economic development levels among cities during regional integration have inadvertently amplified carbon emissions [58]. The positive externalities of increased economic activity on carbon reduction efficiency, or the so-called decoupling effect, have yet to fully manifest. The coefficients for urbanization rate (PU) and population density (PD) are significantly negative, suggesting that the urbanization and concentration of the population during regional integration have started to have a suppressive effect on carbon emissions. Other studies have also supported this finding. The concentration of population and other resource elements facilitates the intensive and rational utilization of energy resources, thereby reducing urban carbon emissions [56]. The coefficient for public fiscal expenditure (PFE) is significantly positive, indicating that during the study period, government support for various economic activities and industrial development increased urban construction levels and could also regulate market resource allocation, indirectly promoting urban carbon emissions [59]. The impact of foreign investment intensity (FDI) on carbon emissions is not significant. This could be due to the differing quality of foreign investment during regional integration, exhibiting both the "pollution haven effect" and the efficiency-enhancing effect of improved energy use, which mutually offset each other, resulting in no clear causal relationship [60]. The coefficients for energy utilization efficiency (NUE) and urban greening rate (UGR) are significantly negative. The former effectively inhibits carbon emissions through enhanced cooperation and resource integration during regional integration, improving energy use efficiency. The latter suppresses carbon emissions through increased urban greening and carbon storage levels, reflecting the widespread emphasis on environmental and ecological quality across Yangtze River Delta cities during regional integration [51]. The road network density (RD) has a significant positive impact on carbon emissions, indicating that the increased traffic demand brought about by regional integration has led to higher energy consumption, thereby increasing urban carbon emissions [58].

5.2. Robust Analysis

This study first analyzes the robustness of the driving variable. In Figure 4, the horizontal axis represents the driving variable, which is the distance from the city to the boundary of the Yangtze River Delta. The vertical axis denotes the density of sample cities, indicating their frequency of occurrence. Each circle represents the observed density of city samples at specific distances from the Yangtze River Delta boundary. The bold line in the middle displays the probability density function on both sides of the cutoff, while the range encompassed by the thin lines above and below constitutes the confidence interval for the probability density function. It can be observed that the confidence intervals of the estimates on both sides of the breakpoint overlap significantly, indicating that the selection of the driving variable meets the randomness condition.

Secondly, we investigated the continuity of control variables, specifically whether there is a discontinuity effect for these variables. The study regresses each control variable as the dependent variable, with the results presented in Table 3. It can be seen that the regression coefficients of the control variables are not significant, indirect indicating that no significant difference occurs at the geographic boundary of the Yangtze River Delta for the control variables. This further confirms the rationality and validity of using GRDD as the estimation method in this study.

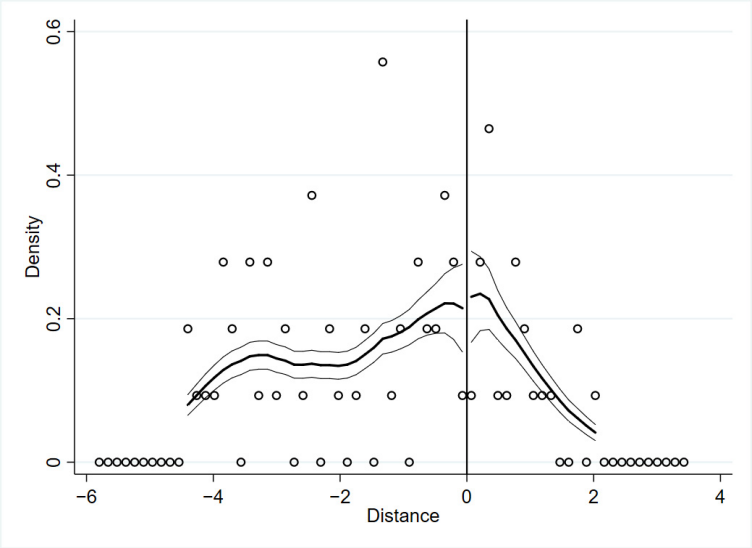


Figure 4. Test for continuity of the driving variable.

Table 3. Test for continuity of control variables.

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	PGDP	PU	PD	PFE	FDI	NUE	RD	UGR
UCL	0.001	0.051	−1.146	3.634	0.008	0.0004	0.001	−0.010
	(0.003)	(0.015)	(0.308)	(0.404)	(0.006)	(0.001)	(0.000)	(0.008)
N	616	616	616	616	616	616	616	616
Time-fixed effect	Y	Y	Y	Y	Y	Y	Y	Y
Spatial fixed effect	Y	Y	Y	Y	Y	Y	Y	Y

Note: standard error in parentheses.

In theory, the selection of different bandwidths can significantly impact the estimation results of breakpoint regression. The study utilizes the IK method [35] to determine the optimal bandwidth as 0.498, indicating that the central points of the sampled cities fall within a range of 49.8 km, inside and outside the boundaries of the Yangtze River Delta. Additionally, Table 4 also presents estimation results using bandwidths that are 1.5 times, 2 times, 4 times, and 8 times the optimal bandwidth, where h represents the different symmetric bandwidths and h* signifies the optimal bandwidth. At a significance level of 1%, regardless of the bandwidth employed, the impact of urban land expansion on carbon emissions remains significant. This suggests that the choice of different bandwidths does not affect the robustness of the core conclusions of this study.

Table 4. Estimation results for different symmetric bandwidths.

Bandwidths	(1)	(2)	(3)	(4)	(5)
	CE				
	h = h* = 0.498	h = 1.5 h* = 0.747	h = 2 h* = 0.996	h = 4 h* = 1.992	h = 8 h* = 3.984
UCL	0.079 ***	0.087 ***	0.050 ***	0.046 ***	0.046 ***
	(0.009)	(0.008)	(0.007)	(0.006)	(0.005)
R^2	0.877	0.881	0.837	0.839	0.785
N	152	200	256	392	584
Control variables	Y	Y	Y	Y	Y
Time-fixed effect	Y	Y	Y	Y	Y
Spatial fixed effect	Y	Y	Y	Y	Y

Note: *** represent coefficients that are significant at the 1% levels, respectively. standard error in parentheses.

The above arguments confirm the robustness and validity of the regression discontinuity estimate approach used in this paper.

5.3. The Inverted U-Shaped Relationship between Urban Construction Land and CO_2 Emissions

To understand whether this relationship follows a strictly linear pattern or an inverted "U" shape (Environmental Kuznets Curve, EKC), this study enhances the original regression model by incorporating a quadratic term of the main independent variable (i.e., the quadratic term UCL2, representing urban construction land area). The regression results are presented in Table 5, where model (1) represents the estimation outcome of the ordinary least squares regression, and models (2), (3), and (4) represent the estimation results of the GRDD. The coefficients of the primary term of UCL are all positively significant at the 1% level, while the coefficients of the quadratic term are all negatively significant at the 1% level. This indicates the presence of an inverted "U" relationship between urban construction land area and carbon emissions. Using the model (4) as the base, the "inverted U-shaped relationship" is tested, and the extreme points are calculated. The results indicate that the amount of urban construction land area associated with the maximum point of carbon emissions falls within the range of the primary explanatory variables ([23.73, 3088]), affirming the robustness of the "inverted U-shaped relationship".

Table 5. Verification results of "inverted U-shaped relationship".

	(1)	**(2)**	**(3)**	**(4)**
		CE		
UCL	0.148 ***	0.143 ***	0.155 ***	0.147 ***
	(0.008)	(0.006)	(0.008)	(0.008)
UCL^2	−0.000 031 ***	−0.000 026 ***	−0.000031 ***	−0.000031 ***
	(0.000)	(0.000)	(0.000)	(0.000)
R^2	0.838	0.752	0.828	0.839
N	616	616	616	616
Control variables	Y	N	Y	Y
Time-fixed effect	Y	N	N	Y
Spatial fixed effect	Y	N	N	Y
Area of UCL corresponding to the peak of carbon emissions (km^2)	2359.739	2718.735	2520.312	2371.613

Note: *** represent coefficients that are significant at the 1% levels, respectively. standard error in parentheses.

The original data show that the urban construction land scale in Shanghai is significantly larger than in other cities. Moreover, apart from Shanghai, most sampled cities did not exhibit significant reductions in the extent of urban construction land expansion. Figure 5 displays linear regression plots (dashed red lines) and curve fitting plots (solid light green lines) illustrating the relationship between urban land development and carbon emissions before and after removing the Shanghai samples. The dark blue dots represent city samples from different time periods, with the horizontal axis showing urban construction land area and the vertical axis showing carbon emissions. From the curve fitting, it can be observed that while the inverted "U" shape is evident, for the vast majority of cities, the inflection point where urban land expansion affects carbon emissions has not yet been reached. Without improving the efficiency of urban construction land utilization, carbon emissions may continue to rise.

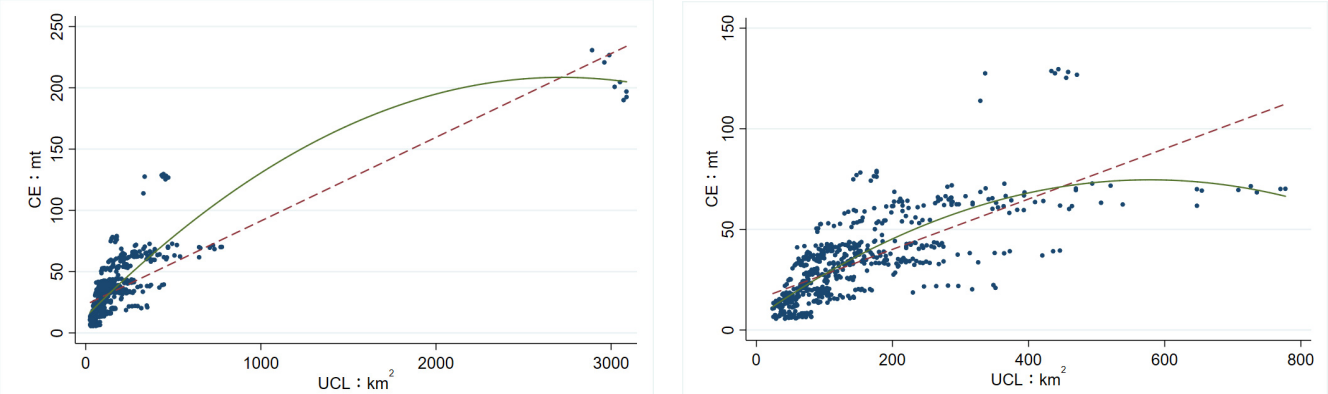


Figure 5. Fitting diagram of urban construction land and carbon emissions including and excluding Shanghai.

5.4. Mechanism Analysis

This study selects two indicators, namely the proportion of the secondary and tertiary industries (NI, unit: %) and the industrial structure upgrade (ISU, unit: %), to describe the transformation of industrial structure. ISU measures the ratio of the output value of the tertiary industry to that of the secondary industry. The changes in consumption pattern are represented by two variables: per capita consumption expenditure (AC, unit: ten thousand yuan) and Engel coefficient (EC, unit: %), which, respectively, reflect the level and structure of residents' consumption. Fiscal scientific and technological investment (STI, unit: hundred million RMB) is considered a measurement indicator for the level of technological investment.

The overall verification and estimation of the impacts of these mechanism variables are conducted using stepwise regression methods. The GRDD method is still employed, along with the same control variables, and quadratic term estimates are included to determine if there are nonlinear effects of mechanism factors. The data on urban construction land and carbon emissions are still denoted as UCL and CE, respectively, but are standardized per capita (UCL_ and CE_) when jointly analyzed with per capita consumption expenditure (AC).

Table 6 presents the relationships between industrial structure, consumption patterns, and technological investment. After controlling for variables and temporal and spatial fixed effects, urban construction land expansion shows significant positive effects on industrial structure, consumption structure, and technological investment, except for the urban Engel coefficient (EC). Combining urban construction land area with each mechanism variable yields results consistent with the baseline regression, demonstrating a significant positive impact of urban land expansion on carbon emissions at the 1% significance level. The coefficients for the proportion of secondary and tertiary industries (NI), industrial structure upgrade (ISU), per capita consumption expenditure (AC), and level of technological investment (STI) are significantly positively correlated with carbon emissions. Furthermore, the significant negative coefficients for the quadratic terms indicate an inverted U-shaped relationship between these four mechanism variables and carbon emissions. As secondary and tertiary industries develop, industrial structure upgrades, per capita consumption expenditure, and technological investment reach certain stages, further increases may mitigate the increase in carbon emissions due to agglomeration effects and technological advancements. Conversely, the urban Engel coefficient exhibits a U-shaped relationship with carbon emissions.

Table 6. Mechanism test.

Explanatory Variable	Industrial Structure				Consumption Pattern				Technological Investment	
	Proportion of the Secondary and Tertiary Industries		Industrial Structure Upgrading		Consumption Level		Consumption Structure		Financial Investment in Science and Technology	
	NI	CE	ISU	CE	AC	CE_	EC	CE	STI	CE
UCL(UCL_)	0.006 **	0.047 ***	0.001 ***	0.047 ***	0.040 ***	0.160 ***	−0.003 ***	0.047 ***	0.131 ***	0.047 ***
	(0.003)	(0.005)	(0.000)	(0.005)	(0.019)	(0.007)	(0.001)	(0.005)	(0.011)	(0.005)
R^2	0.262	0.784	0.453	0.784	0.871	0.742	0.229	0.784	0.964	0.784
NI		10.555 **								
		(4.716)								
NI^2		−0.057 **								
		(0.026)								
R^2		0.758								
ISU				23.441 ***						
				(5.563)						
ISU^2				−8.619 ***						
				(2.207)						
R^2				0.842						
AC						0.202 ***				
						(0.062)				
AC^2						−0.030 **				
						(0.014)				
R^2						0.554				
EC								−3.202 ***		
								(0.464)		
EC^2								0.028 ***		
								(0.005)		
R^2								0.797		
STE										0.355 ***
										(0.019)
STE^2										−0.0004 ***
										(0.000)
R^2										0.923
N	616	616	616	616	616	616	616	616	616	616
Control variables	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Time-fixed effect	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Spatial fixed effect	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y

Note: **, and *** represent coefficients that are significant at the 5%, and 1% levels, respectively. standard error in parentheses.

The study confirms that urban construction land expansion enhances non-agricultural industrial levels, promotes industrial structure upgrades, influences per capita consumption levels, drives upgrades in consumption structure, and increases the level of technological investment during the integration process of the Yangtze River Delta.

6. Discussion

Our study found that carbon emissions in the Yangtze River Delta regional integration process from 1997 to 2007 initially increased and then showed a trend towards deceleration, with certain cities like Shanghai even reaching or showing a decline in their emissions peak. Feng et al. (2024) have observed that the demand for urban construction land and carbon emissions increased during regional integration. In the Beijing–Tianjin–Hebei (BTH) region, the demand for urban construction land gradually increased between 2002 and 2019, while carbon emissions increased 2.5 times, from 183 million tons to 464 million tons [56]. The research of Chen and Huang (2016) has shown that the European Union enlargement reduced pollution emissions in its cities [61]. Similarly, Ran et al. (2023) found that the regional integration enlargement in the Yangtze River Delta (YRD) in 2010 and 2013 had a mitigating effect on carbon emissions [62]. Another study treats the expansion of the Yangtze River Delta Urban Economic Coordination Council as a quasi-natural experiment, using the same period data as ours. It also concluded that regional integration enlargement of the YRD reduced carbon emissions [63]. However, our study does not focus on regional integration enlargement but rather emphasizes the impact of regional integration policies on construction land and their subsequent effect on carbon emissions.

We used a GRDD analysis and highlighted the role of construction land expansion. This approach differs from the traditional RDD method and natural experiments, which do not consider geographical factors. Our findings confirm that urban construction land expansion significantly contributes to carbon emissions during the regional integration of the YRD. This contribution is notably higher than in cities outside the YRD. Regional economic integration amplifies the impact of carbon emissions due to the agglomeration effects and intensified socio-economic interactions brought about by the expansion of construction land. Tan et al. (2023) have validated the positive impact of urban construction land in the Wuhan metropolitan area while also suggesting that a more sustainable regional integration policy has a higher potential for emission reduction [53].

Our further analysis reveals a robust inverted U-shaped relationship between the expansion of urban construction land and carbon emissions. Lv et al. (2023) found that the intensive use of construction land showed an overall increasing trend, with a slower growth rate between 2006 and 2011 and a significantly higher growth rate between 2012 and 2020 [29]. Deng et al. (2011) discovered that the impact of construction land expansion on carbon emissions showed a declining trend in coastal areas of China [11]. In the major metropolitan areas of the United States, especially innovation hubs, per capita carbon emissions are relatively low and have been decreasing [64]. These findings indicate that the use of construction land in regional integration can follow a more sustainable development model. Reasonable regulation of land use to achieve carbon reduction targets has become an important measure for countries worldwide to achieve sustainable development. Chuai et al. (2015) used a linear programming model to optimize land use structure and found that limiting urban land scale plays a key role in carbon reduction [65]. Li et al. (2019) also highlighted that the reduction and control of construction land area currently being implemented in Shanghai is a viable policy tool [28].

In the early stages of regional integration of the Yangtze River Delta, land planning often neglected the adverse outputs of construction land use and lacked unified coordination among local municipalities. This inconsistency between construction land use policies and carbon reduction policies persisted. As the integration of the Yangtze River Delta region rose to a national strategic level, the central government recognized these issues. In 2023, the State Council approved the "Overall Plan for Ecological and Green Integrated Development Demonstration Zone in the Yangtze River Delta (2021–2035)," emphasizing the synergistic role of land use policies and green development policies.

Therefore, local governments should prioritize restricting the speed of urban construction land expansion during regional integration. It is crucial to delineate reasonable urban development boundaries, promote intensive land use, and enhance the carbon sequestration capacity of urban ecological land. Integrating urban land development with population and economic growth can help mitigate further carbon emissions from population concentration. Promoting sustainable urban renewal, efficiently utilizing limited increments of construction land, and focusing more on reducing and activating existing land resources are essential for ensuring socio-economic development. These efforts contribute to achieving low-carbon development through regional integration.

After verifying a significant link between the expansion of construction land and carbon emissions, studies have further explored the mechanisms through which construction land affects carbon emissions. Consistent with previous research, the industrial transformation has been confirmed as a conduit for carbon emissions in regional integration. The study of Yan et al. (2023) also noted that the impact of industrial structural optimization on carbon emissions is closely related to its efficiency [63]. Our study not only focuses on industrial structural optimization but also emphasizes the mediating role of these factors, including technological investment and consumption patterns, in the impact of construction land on carbon emissions during the integration process in the YRD. Further investigation reveals the non-linear impacts of industrial transformation, technological investment, and residents' consumption patterns on carbon emissions. Other studies did not specifically analyze construction land, but they still believe that it is crucial to prioritize investment in

green technology innovation to enhance carbon reduction effects [66]. Regional integration facilitates learning from and adopting successful experiences of carbon reduction in surrounding areas [67]. However, it is important to note that regional integration can enable developed cities to promote industrial structural optimization and attract higher-quality elements, achieving lower carbon emissions. Underdeveloped cities may also become pollution havens for lower-end elements [68]. If attention is not given to the combination of intensive construction land use, low-carbon industrial transformation, green technological investments, and changes in consumption habits during regional integration, regional integration may have limited impact, similar to its inability to affect carbon dioxide emissions reductions in Cambodia, Malaysia, Indonesia, and Thailand [69].

In certain regions of the Yangtze River Delta, the secondary industry holds a relatively high proportion, yet the development of clean energy technologies remains comparatively lagging. There remains considerable potential for enhancing carbon reduction efforts and attaining peak carbon emissions. We suggest that cities in the Yangtze River Delta should formulate differentiated emission reduction policies based on their own resource endowments, locational advantages, and existing development levels. This approach aims to maximize the pivotal role of intermediary factors in influencing mechanisms and to establish a low-carbon industrial system in the region. Deepening inter-regional industrial division of labor cooperation, enhancing efficiency in the allocation of factors both between and within industries, and fostering a high-level pattern of coordinated development. Higher-tier cities, serving as demonstrations and leaders in regional integration, can prioritize the development of new energy sources, new materials, high-tech industries, and high-end services. Additionally, governments should increase funding support for low-carbon technology research and development to promote energy conservation and carbon emission reduction through technological advancement while mitigating potential "rebound effects" from technological innovation. Promoting institutional innovation in the demonstration area for ecological and green integrated development in the Yangtze River Delta, constructing a green and low-carbon development system, and establishing green barriers. Enhancing the development of digital and green infrastructure, promoting the sharing of public services, encouraging citizens to adopt low-carbon consumption habits, optimizing consumption patterns, practicing green and low-carbon lifestyles, and offsetting the increasing trend of carbon emissions with rising income levels.

7. Conclusions

Using the administrative boundaries formally delineated by the Yangtze River Delta Economic Coordination Association as geographical discontinuities, this study employs the GRDD method to investigate the impact of urban construction land expansion on carbon emissions during the Yangtze River Delta region integration.

The main conclusions are as follows: Firstly, urban construction land expansion significantly contributes to urban carbon emissions, with robust regression results. Controlling for variables and fixed effects, both carbon emissions and urban construction land area in cities within the Yangtze River Delta region are higher compared to cities outside the region. For every 1% increase in urban construction land area, carbon emissions increase by 0.047%. Secondly, there is an inverted "U"-shaped relationship between urban construction land expansion and carbon emissions. Most cities have not yet reached the turning point where the impact of urban construction land expansion on carbon emissions starts to decline. Achieving peak carbon emissions during the integrated development of cities in the Yangtze River Delta region remains both challenging and promising. Thirdly, mechanism analysis indicates that urban construction land expansion affects carbon emissions through industrial structural transformation, consumption patterns, and technological investments. This impact also exhibits a non-linear trend, emphasizing the need for strengthened policies to ensure the positive role of intermediary factors in carbon reduction.

Additionally, the study notes that within China's government-led integration process, an increasing number of cities are eager to participate in integration to achieve higher-

quality development. Enlargement is expected to become the norm in regional integration development, highlighting the necessity of establishing a coordinated mechanism for carbon reduction and construction land utilization among cities.

It is worth noting that the study focused exclusively on the more developed Yangtze River Delta region integration as its research subject, spanning the early stages of development. However, due to unforeseen factors such as multiple enlargements and the impact of epidemics, the study's timeframe was limited. Furthermore, the study did not delve deeper into the complex mechanisms through which different types of construction land affect carbon emissions and did not include the analysis of non-construction land, such as the carbon sequestration role of green space in terms of area and quality within an analytical framework.

Future research could compare regional integrations in different areas and consider the impacts of regional integration enlargement. Additionally, deeper exploration could be conducted into the heterogeneous effects of construction land on carbon emissions and intermediary mechanisms during the regional integration process. Using more appropriate methods, future studies could investigate how different types of construction land and non-construction land influence carbon emissions from the perspective of coordinated development in digital and green development. This can provide more refined guidance for the formulation of spatial planning and the implementation of related policies for green development in regional integration.

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Conflicts of Interest: The authors declare no conflicts of interest.

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