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How Much Green Benefit Does Urbanization Generate?

-- Evidence from Carbon Productivity and Regional Heterogeneity Analysis

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Abstract

Based on panel data from 30 provinces in China from 2010 to 2022, this study employs a two-way fixed effects model to explore the impact of urbanization on carbon productivity and its regional heterogeneity from multiple dimensions.The findings reveal that population urbanization generally inhibits carbon productivity, industrial urbanization has a positive green effect, and the national average effect of land urbanization is not significant. There is significant regional differentiation, with the crowding effect of population agglomeration prominent in the eastern region, the empowering effect of land and industrial urbanization significant in the western region, and various effects balanced in the central region. After the policy milestone in 2015, the marginal impact of urbanization gradually declined. Therefore, it is necessary to formulate policies for urbanization and low-carbon development according to local conditions, build a regional coordinated development system, and promote the transformation of urbanization models towards high-quality and green development.

Keywords

Urbanization; Carbon Productivity; Regional Heterogeneity; Multidimensional Urbanization.

1. Introduction

1.1. Research Background

Promoting green and low-carbon economic and social development is a key aspect of achieving high-quality development. After China clearly set the major strategic goals of "carbon peaking" and "carbon neutrality", economic and social development has comprehensively shifted to a new stage of high-quality development guided by ecological priority and green development. Against this backdrop, urbanization, as the essential path and core driving force of China's modernization, urgently needs to transform its development model from the previous extensive expansion focusing on scale and speed to the intensive improvement focusing on quality and efficiency. Traditional urbanization, while creating economic miracles, has also brought about a series of issues such as resource consumption and environmental pressure. Therefore, exploring how the process of urbanization can be coordinated with the ecological environment and how it can be upgraded from a "growth engine" to a "green engine" is not only related to the timely achievement of the "dual carbon" goals but also the core proposition of promoting people-centered new urbanization in the new era. In this context, scientifically and accurately assessing the "green benefits" of urbanization has become an important topic that combines theoretical frontier and policy urgency.

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1.2. Problem Statement

Under the dual constraints of the "dual carbon" strategy and high-quality development, improving the quality of urbanization has become the key to unlocking the potential for green growth. However, current research faces two core bottlenecks: first, it is difficult to accurately quantify the green benefits of marginal changes in urbanization, and second, there is a lack of systematic revelation of the spatial differentiation of these benefits. Specifically, this study aims to progressively answer two core scientific questions: first, "how big is the effect," that is, what is the net marginal effect of a 1% increase in urbanization rate on carbon productivity? Existing research has mostly focused on demonstrating the "direction" and "significance" of the impact, but there is still a lack of reliable quantitative estimates for the net impact of a specific marginal amount of "1% change," and this precise value is crucial for assessing the quality and benefits of urbanization and making scientific decisions; second, "where does the effect differ," that is, whether the above marginal effects exhibit significant regional heterogeneity? What is the spatial pattern and formation logic? China’s regional development conditions vary greatly, and systematically depicting this "regional heterogeneity map" and exploring its key underlying causes are prerequisites for translating overall conclusions into differentiated and actionable policies.

Therefore, this study aims to break through the limitations of aggregate analysis and overall average, adopting a marginal perspective based on "1% change in urbanization rate" and using "carbon productivity" as the core efficiency yardstick. By constructing a rigorous econometric model, it precisely answers the two core questions of "effect size" and "spatial differentiation" in turn, thus providing solid empirical evidence for mapping a high-quality development path for urbanization tailored to local conditions.

1.3. Research Significance

The value of this study is reflected at both theoretical and practical levels.

In terms of theoretical significance, firstly, the study shifts the evaluation of the environmental effects of urbanization from the traditional single "pressure perspective" to the innovative "efficiency perspective", with "carbon productivity" as the core dependent variable, which helps to more comprehensively understand the interactive relationship between urbanization and green development. Secondly, the study aims to scientifically quantify the marginal effects of urbanization changes, advancing the existing analysis from simple qualitative judgment to precise quantitative evaluation, providing more refined empirical evidence for relevant theoretical research. Finally, through systematic regional heterogeneity analysis, the study helps to reveal the specific contextual conditions dependent on which the green effects of urbanization are exerted, enriching the spatial political economy connotation of the environmental effects of urbanization in China.

In practical terms, the research conclusions can provide direct and effective policy implications for the high-quality development of urbanization under the background of "dual carbon" goals. By accurately calculating the green benefits of urbanization enhancement across the country and different regions, it can provide scientific cost-benefit references for governments at all levels to formulate reasonable urbanization development goals. More importantly, revealing regional heterogeneity can strongly support the design of differentiated and targeted regional policies. For example, it can indicate the focus of quality improvement and efficiency enhancement for the eastern region, avoid potential ecological risks for the western region, and provide a reliable basis for designing corresponding compensation mechanisms, thereby promoting the formation of a new pattern of green development of territorial space featuring complementary advantages and win-win cooperation.

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1.4. Research Approach and Framework

This study adopts a core technical route of "theoretical analysis, model construction, empirical testing, and conclusion extraction": Firstly, it systematically reviews the relevant theories and existing research on the impact of urbanization on carbon productivity, clarifying the intrinsic correlation mechanism of core variables. Secondly, based on provincial panel data (2012-2022), a two-way fixed effects panel model is constructed to accurately quantify the marginal effect of a 1% change in urbanization rate on carbon productivity (core green benefits). Thirdly, regional grouping variables are introduced to compare and analyze the heterogeneous characteristics of the eastern, central, and western regions. Finally, robustness checks such as replacing core variables and adjusting sample intervals are conducted to verify the reliability of the conclusions. Ultimately, research conclusions are drawn and targeted policy recommendations are proposed.

Following the aforementioned approach, the structure of this paper is arranged as follows: The first part is the introduction, which elaborates on the research background, raises core issues, clarifies the research significance and framework; the second part systematically reviews relevant literature and provides commentary; the third part elaborates on the theoretical analysis framework and proposes research hypotheses; the fourth part details the research design, including model setting, variables, and data; the fifth part presents empirical results, including benchmark regression, endogeneity tests, robustness checks, and regional heterogeneity analysis; the sixth part summarizes the full text, refines research conclusions, summarizes core findings, and proposes differentiated policies for urbanization and low-carbon coordinated development.

2. Literature Review

2.1. Literature Combing

The relationship between urbanization and the ecological environment is a core issue in development economics and regional science. In the context of China's new era of advancing the "carbon peak and carbon neutrality" strategy and high-quality development, exploring the green benefits of the urbanization process is of crucial significance. This paper focuses on "carbon productivity" as a core indicator to measure green benefits, aiming to assess the marginal effects and regional heterogeneity of urbanization impacts. Existing research has provided a solid foundation for this, and its evolution is mainly reflected in three dimensions: theoretical cognition, research perspectives, and spatial analysis.

On the theoretical cognition front, scholarly cognition has deepened from the conflict theory to the view of complex nonlinear correlations. Early studies mostly emphasized the resource depletion and environmental pressures brought by urbanization. For example, Qiu and Huang (2020) found a significant positive correlation between urbanization and haze pollution[1], while Liang et al. (2017) reached the opposite conclusion that growth in the urbanization rate markedly curbs haze pollution[2]. A growing body of literature has verified the nonlinear nature of this correlation. For instance, Qiu and Huang (2020) detected an inverted U-shaped curve in eastern China[1], whereas Liang et al. (2017) identified an N-shaped curve[2]. Research specifically targeting carbon productivity has likewise confirmed such nonlinear patterns. Wang (2021) discovered that population urbanization exerts a two-stage effect on carbon productivity: strong facilitation followed by weak facilitation, while land urbanization presents a facilitation-then-decoupling relationship[3]. Zhu et al. (2025) noted that industrial intelligence substantially lifts carbon productivity, alongside the moderating effect and threshold effect of environmental regulations[4]. Feng et al. (2025) argued that city size imposes dynamic nonlinear impacts on total factor carbon productivity, and better transport infrastructure reinforces such nonlinear effects[5]. Jiao and Yan (2016) further measured and

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concluded that the coupling coordination degree between urbanization and carbon productivity remains generally at a low level[6].

On the research perspective front, relevant literature witnesses a progressive shift from the single focus on environmental pressure to developmental efficiency, and from a one-dimensional scale perspective to multidimensional connotations of urbanization. First, academic focus has turned to comprehensive indicators integrating economic and environmental efficiency. Lyu et al. (2019) examined how urbanization affects energy intensity[7]; Hu and Li (2024) found that penetration of digital industries can advance common prosperity via industrial structure upgrading[8]. Second, scholars widely recognize urbanization as a compound multidimensional concept. Wang et al. (2019) analyzed its differentiated carbon emission impacts across population, land and economic dimensions[9]. Zhang and Yang (2020) and Zhu et al. (2020) similarly stressed the heterogeneous influences of different urbanization dimensions[10,11]. From the dual dimensions of urbanization scale and urban quality, Li et al. (2024) found that coordinated urban development displays an east-high and west-low spatial pattern accompanied by obvious path dependence[12]. Xiong and Xu (2018) constructed an evaluation system for new-type urbanization and uncovered prominent cross-regional disparities[13].

On the spatial analysis front, regional heterogeneity has been widely acknowledged as a consensus within this research field. A wealth of empirical evidence has verified pronounced cross-regional differences. Lyu et al. (2019) documented that urbanization exerts the strongest negative influence on energy intensity in central China and the weakest in eastern China[7]. Qiu and Huang (2020) pointed out that urbanization generates vastly different haze-relevant effects across eastern, central and western China[1]. Yang (2016) and Zhu et al. (2020) reached consistent findings of regional heterogeneity when investigating urbanization's economic growth spillovers[11,14]. Likewise, Zhu et al. (2022) drew identical conclusions in their research on how urbanization affects rural revitalization[15].

Studies covering other dimensions also corroborate the existence of regional differentiation. Lyu and Fan (2024) found that urbanization substantially raises local rural households' income yet widens the income gap among rural residents[16]. Zhong and Yao (2023) revealed that land finance enlarges the urban-rural income gap, and such effects grow sequentially from eastern to central and then western China; by contrast, urbanization itself helps narrow this divide[17]. Based on panel data of the Yangtze River Delta, Ni et al. (2023) concluded that urbanization mitigates urban-rural poverty yet generates significant spatial spillover effects[18]. Wang et al. (2019) identified evident population urbanization agglomeration effects across the Yangtze River Economic Belt, where adjacent regions have forged mutually promotive interactive relationships[19]. Hu and Cao (2018) demonstrated that urbanization delivers positive gains to the tourism economy, though such benefits are weaker in eastern China than in central and western China[20]. Yu et al. (2014) built a comprehensive scoring framework for urbanization and found that the growth contribution of each urbanization dimension differs substantially across the three major regional blocks[21]. Wang (2013) illustrated that population and spatial urbanization drive economic growth mainly via the investment transmission channel, with distinct spatial disparities between eastern China and inland central and western regions[22].

In addition, Li et al. (2012) categorized seven distinctive development models for China's urbanization advancement and underscored its state-led development features[23]. Zhu et al. (2011) estimated that every one-percentage-point rise in the urbanization rate underpins approximately 7.1% economic growth[24]. Wu (2017) emphasized the coupling coordination between people-centered urbanization and the equalization of basic public services[25]. Collectively, these studies demonstrate that urbanization's socioeconomic and environmental impacts vary substantially across different development stages, geographic regions and multidimensional urbanization dimensions.

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2.2. Literature Review

By reviewing relevant literature, it is found that existing studies still have some deficiencies. On the one hand, most studies focus on the impact of urbanization on environmental pressures such as carbon emissions and total pollution, but fail to fully define and measure its "green benefits" based on the comprehensive efficiency indicator of "carbon productivity". The research perspective needs to be deepened. On the other hand, existing analyses mostly concentrate on examining the overall direction and significance of impacts, lacking precise quantification of the specific marginal effects generated by "1% changes in urbanization rate", and seldom systematically investigate the heterogeneity of these marginal effects across different regions such as the eastern, central, and western regions, as well as their multidimensional driving mechanisms within a unified framework. Therefore, this paper aims to fill the aforementioned gaps, with carbon productivity as the core, to construct an econometric model to precisely quantify the marginal green benefits of urbanization, and deeply reveal its regional differentiation characteristics, in order to provide a basis for differentiated policies.

3. Theoretical Mechanism and Research Hypothesis

The process of urbanization is essentially the spatial reorganization and upgrading of production factors. Its core essence of high-quality development is highly isomorphic with the technological revolutionary breakthroughs and innovative factor allocation emphasized by "new-quality productive forces". With technological innovation as its core driving force, new-quality productive forces promote the transformation of industries towards high-end, intelligent, and green development. By optimizing the allocation of factors such as labor, capital, technology, and data, they enhance overall economic efficiency. From this theoretical perspective, urbanization becomes a crucial spatial domain for nurturing and hosting new-quality productive forces. Specifically, urbanization provides talent, knowledge, and market infrastructure for the innovation and diffusion of green technologies through the "agglomeration economy" effect. The implementation of green technologies can directly increase economic output per unit of carbon emissions (carbon productivity). Through demand upgrading and supply optimization, it drives the evolution of industrial structure towards low-energy consumption, high-value-added modern service industries and advanced manufacturing industries, reducing the carbon emission intensity per unit of output from a structural level and thus enhancing carbon productivity. At the same time, an intensive and smart urban form itself represents an innovative allocation of production factors, which can systematically improve the utilization efficiency of resources such as energy and land, further strengthening the effect of enhancing carbon productivity. Therefore, the process of high-quality urbanization is precisely the process of transforming the potential of new-quality productive forces into actual green output—that is, the improvement of carbon productivity (the green benefit focused on in this study). Based on this, the following hypothesis is proposed:

H1: The improvement of urbanization level has a significant positive marginal effect on carbon productivity.

The effect of new-quality productive forces empowering economic development is not homogeneous, and its depth of exertion depends deeply on the comprehensive ecosystem composed of regional factor endowments, industrial foundation, and institutional environment. China’s vast territorial space exhibits significant gradient development differences: the eastern coastal regions have absolute advantages in technological innovation resource agglomeration, industrial structure sophistication, market mechanism maturity, and infrastructure integrity, and their urbanization process can more efficiently absorb and integrate key elements of new-quality productive forces; the central region is in the stage of deepening industrialization and

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undertaking industrial transfer; the western region, limited by geographical location, initial development level, and industrial structure, has relatively weaker levels of urbanization factor agglomeration and innovation network intensity. This systematic difference in ecosystem intensity among regions inevitably leads to different efficiency and smoothness in the transmission mechanism of urbanization enhancing carbon productivity, resulting in an uneven spatial pattern of ultimate green benefits. Based on this, the following hypothesis is proposed:

H2: The impact of urbanization on carbon productivity exhibits significant regional heterogeneity, with distinct differences in the direction and intensity of the effect across the eastern, central, and western regions.

4. Econometric Model and Variable Explanation

4.1. Model Construction

To precisely quantify the marginal effect of urbanization on carbon productivity and examine regional heterogeneity, this study constructs a two-way fixed effects panel data model. The benchmark regression model is set as follows:

$$y_{it}=\alpha+\beta_1 x_{1it}+\beta_2 x_{2it}+\beta_3 x_{3it}+\gamma_1 x_{4it}+\gamma_2 x_{5it}+\mu_i+\lambda_t+\varepsilon_{it} \quad (1)$$

In this context, y_{it} represents the dependent variable, indicating the carbon productivity of province i in year t. x_{1it} , x_{2it} and x_{3it} are the core explanatory variables, respectively representing the population urbanization rate, land urbanization rate, and industrial urbanization rate of province i in year t. x_{4it} and x_{5it} are control variables, α is a constant term, μ_i and λ_t represent individual fixed effects and time fixed effects, respectively, and ε_{it} denotes random error.

4.2. Variable Selection Explanation

Table 1. VariableDefinitions

Variable Type	Variable Name	Variable Symbol	Calculation Method
Dependent variable (y)	Carbon Productivity	CP	Regional gross domestic product divided by regional carbon dioxide emissions (unit: 100 million yuan / ten thousand tons)
Core explanatory variable (x_1)	Population Urbanization Rate	PUR	Urban population divided by year-end permanent resident population
Core explanatory variable (x_2)	Land Urbanization Rate	LUR	Built-up area divided by administrative regional area
Core explanatory variable (x_3)	Industrial Urbanization Rate	IUR	Sum of the added value of secondary and tertiary industries divided by regional gross domestic product
Control variable (x_4)	Energy Consumption Structure	ECS	Coal consumption divided by total energy consumption
Control variable (x_5)	Economic Development Level	ln(PGDP)	Natural logarithm of regional per capita gross domestic product

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(1) Dependent Variable. Carbon Productivity (CP): This study operationalizes "green benefits" as the efficiency of decoupling economic growth from carbon emissions, namely carbon productivity. This indicator is defined as the ratio of regional GDP to carbon dioxide emissions, and its economic meaning is the "economic value generated per unit of carbon emissions," which can comprehensively reflect the core efficiency of green and low-carbon development in a region. A higher value indicates that the region pays a smaller carbon emission cost while creating economic wealth, and the green benefits are greater. Compared to simple indicators of total carbon emissions or intensity, this indicator is more in line with the dual requirements of balancing economic growth and carbon emission reduction in the context of high-quality development.

(2) Core explanatory variables. To comprehensively depict the multidimensional connotation of urbanization, this study selects core explanatory variables from three dimensions: (1) Population urbanization rate: This indicator is the most core and universal measure of urbanization, reflecting the scale and progress of population aggregation from rural to urban areas, and directly reflecting the transformation of urbanization's social form. (2) Land urbanization rate: Reflecting the physical scale of urban spatial expansion. Its impact is dual: extensive expansion may reduce land use efficiency, increase commuting and energy consumption, and inhibit carbon productivity; while intensive and intelligent land use may improve efficiency. (3) Industrial urbanization rate: This indicator measures urbanization from the perspective of economic structure, reflecting the degree of labor transfer from agriculture to the secondary and tertiary industries, and is a manifestation of the strength of urbanization's industrial support and endogenous driving force.

(3) Control variables. Energy consumption structure (ECS): The proportion of coal in primary energy consumption. Controlling this variable allows for the isolation of changes in carbon emission intensity due to differences in energy structure, thereby more purely capturing the efficiency gains brought about by changes in urbanization patterns. Economic development level (ln(PGDP)): Logarithmically transformed per capita GDP, used to control the impact of economic development stages. Controlling this variable allows for the isolation of pure green benefits brought about by the urbanization process.

4.3. Data Sources and Descriptions

This study utilizes panel data from 30 provinces in China (excluding the Xizang Autonomous Region, Hong Kong, Macao, and Taiwan) spanning from 2010 to 2022, with a total of 390 observations. The data is sourced from the China Statistical Yearbook, China City Statistical Yearbook, China Emissions Accounting Database (CEADs), China Energy Statistical Yearbook, statistical yearbooks of various provinces and cities, and public data from the National Bureau of Statistics. For individual missing data, the study employs the moving average method for imputation.

5. Empirical Results and Analysis

5.1. Descriptive Statistical Analysis and Multicollinearity Test

The descriptive statistical results of the main variables in this study are presented in Table 2. The dependent variable, carbon productivity (y), has a mean of 0.9148, with a maximum value of 6.6698 and a minimum value of only 0.0793, indicating a significant disparity in green development efficiency among China's provinces and highlighting the prominent feature of uneven regional development. In terms of core explanatory variables, the population urbanization rate has a mean of 0.5949, indicating an overall medium stage of urbanization development with relatively mild inter-provincial differentiation. The land urbanization rate has a mean of only 0.0214, but with significant extreme differences, suggesting notable

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variations in the pace and scale of urban construction land expansion across provinces. The industrial urbanization rate has a mean of 0.9026, indicating that non-agricultural industries have occupied an absolute dominant position at the national level. Among the control variables, the energy consumption structure has a mean of 0.9498, reflecting that China's energy consumption during the sample period is still highly dependent on fossil fuels such as coal. The logarithmically transformed per capita GDP has a mean of 10.8392 and a standard deviation of 0.4915, indicating economic disparities among provinces. The significant dispersion of variables provides a solid and reliable data basis for subsequent regional heterogeneity analysis.

Table 2. Descriptive Statistics Results

Variable	Obs	Mean	Std. Dev.	Min	Max
y	390	0.9148	0.8539	0.0793	6.6698
x_1	390	0.5949	0.1239	0.3380	0.8958
x2	390	0.0214	0.0349	0.0002	0.1959
x3	390	0.9026	0.0520	0.7385	0.9978
x4	390	0.9498	0.5756	0.0115	6.2109
x5	390	10.8392	0.4915	9.4778	12.2396

To ensure the reliability of model estimation, this study employs the variance inflation factor (VIF) method to test for multicollinearity issues. The test results, as shown in Table 3, indicate that the maximum VIF value for all variables is 6.58, with an average of 3.48, both significantly below the empirical threshold of 10. This demonstrates that there is no severe multicollinearity issue between the explanatory and control variables selected in this paper, confirming that the model setup is reasonable and suitable for subsequent regression analysis.

Table 3. Variance Inflation Factor (VIF)

Variable	VIF	1/VIF
x_1	6.58	0.151872
x3	4.6	0.217572
x5	2.77	0.360638
x2	2.26	0.441965
x4	1.19	0.837766
Mean VIF	3.48	

5.2. Benchmark Regression Analysis

This paper adopts a two-way fixed effects model and uses province clustering robust standard errors to correct for within-group serial correlation and heteroskedasticity issues, gradually incorporating core explanatory variables and control variables to conduct benchmark regression. This method not only helps to test the robustness of the model but also further enhances the reliability of the research. The specific empirical results are shown in Table 4.

Table 4 presents Model (1) showing the regression analysis results without any control variables. The results indicate that the coefficient of the industrial urbanization rate is 6.4475, which is significantly positive at the 5% statistical level. This suggests that, purely from the perspective of urbanization structure, an increase in the proportion of non-agricultural industries can effectively enhance carbon productivity, preliminarily confirming the green dividends of industrial transformation. The coefficient of the population urbanization rate is negative but fails to pass the significance test, and the coefficient of the land urbanization rate

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is also insignificant, reflecting that the effects of population agglomeration and urban land expansion are still unclear under this simple specification.

Table 4. Baseline Regression Results

Variable	y		
	(1)	(2)	(3)
x_1	-10.5598		-13.9169*
	(0.2080)		(0.0860)
x_2	-6.5752		-11.4525
	(0.7110)		(0.4510)
x_3	6.4475**		4.0014*
	(0.0350)		(0.0650)
x_4		-0.3333**	-0.2878**
		(0.0480)	(0.0150)
x_5		1.0663**	2.3615***
		(0.0380)	(0.0090)
_cons	0.3671	-10.1179*	-19.6084***
	(0.9150)	(0.0550)	(0.0020)
Province/Year Fixed Effects	YES	YES	YES
N	390	390	390
R^2	0.5588	0.4786	0.6659

Note: ***, **, * indicate significance at the 1%, 5%, and 10% levels, respectively. P values are provided in parentheses, the same below.

Model (2) further incorporates two control variables, namely, the structure of energy consumption and the level of economic development, to strip away the interference factors of energy structure and economic stage. It can be observed that the coefficient of the energy consumption structure is significantly negative at the 5% level, meaning that a higher proportion of high-carbon energy sources such as coal leads to lower regional carbon productivity, which is consistent with theoretical expectations. The coefficient of the level of economic development is significantly positive at the 5% level, indicating that economic development can provide material and technological support for green and low-carbon transformation, thereby facilitating the improvement of carbon productivity.

Model (3) is the complete benchmark model, incorporating both three-dimensional urbanization and all control variables to generate credible regression estimates. The regression results show that: firstly, the coefficient of the population urbanization rate is 13.9169, which is significantly negative at the 10% level. This suggests that after comprehensively controlling for energy structure and economic level, the continuous population agglomeration towards cities inhibits the improvement of carbon productivity. The reason for this is that large-scale population agglomeration will lead to increased energy consumption and carbon emissions in areas such as commuting, living, and construction, forming a significant "crowding effect" that offsets the scale efficiency advantages brought by population agglomeration. Secondly, the coefficient of the land urbanization rate is -11.4525, but fails to pass the significance test. The nationwide land expansion has no significant average impact on carbon productivity. This paper infers that this result is not due to the ineffectiveness of land urbanization, but rather due to opposite effects of land development in different regions, where positive and negative effects offset each other. Subsequent regional heterogeneity analysis will verify this. Thirdly, the coefficient of the industrial urbanization rate is 4.0014, which is significantly positive at the 10%

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level. An increase in the proportion of non-agricultural industries can continuously optimize the regional industrial structure, reduce the overall carbon emission intensity, and release green benefits. However, as the level of industrial urbanization continues to rise, the marginal gains have declined. Fourthly, the two control variables exhibit stability. The energy consumption structure is significantly negative at the 5% level, while the level of economic development is significantly positive at the 1% level, which is highly consistent with economic theory and real-world characteristics.

Overall, the benchmark regression results indicate that extensive population urbanization is not conducive to enhancing carbon productivity, while industrial urbanization exhibits a stable positive green effect. However, the national average effect of land urbanization is obscured by regional differences. This result partially confirms research hypothesis H1. The reason lies in the fact that urbanization is a multidimensional and complex concept, with divergent effects in different dimensions. The negative effect of population urbanization offsets some of the positive effects, leading to deviations between the overall average characteristics and theoretical expectations. It also suggests that the impact of three-dimensional urbanization on carbon productivity exhibits complex and obvious spatial differentiation characteristics across Chinese provinces.

5.3. Analysis of Regional Heterogeneity

There are significant disparities in resource endowments, industrial structures, stages of urbanization development, and the intensity of low-carbon policy implementation across different regions in China. The mechanism by which three-dimensional urbanization affects carbon productivity inevitably exhibits differentiated characteristics. To verify the research hypothesis H2, this paper divides the 30 provinces into three major regions: the eastern, central, and western regions, according to the commonly used classification criteria, and conducts sub-sample regression. The results are presented in Table 5.

Table 5. Results of Regional Heterogeneity Regressions

Variable	y		
	Eastern region	**Central region**	**Western region**
x_1	-17.2265**	2.1736	-4.6727*
	(0.0410)	(0.6820)	(0.0780)
x_2	-25.9699	-27.2355	143.6696***
	(0.1380)	(0.7330)	(0.0010)
x_3	-3.3056	2.4995	4.3190*
	(0.5550)	(0.1710)	(0.0730)
x_4	-3.2996***	-0.2064***	-0.8214***
	(0.0090)	(0.0040)	(0.0010)
x_5	3.9769**	1.0307*	0.4880
	(0.0290)	(0.0570)	(0.1960)
_cons	-24.3009*	-12.7211**	-5.8480
	(0.0920)	(0.0120)	(0.2700)
Province/Year Fixed Effects	YES	YES	YES
N	143	104	143
R^2	0.8075	0.8688	0.8251

From the perspective of population urbanization , the coefficient for the eastern region is -17.2265, which is significantly negative at the 5% level; the coefficient for the western region is -4.6727, which is significantly negative at the 10% level; the coefficient for the central region

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is positive but not significant. The urbanization development in the eastern region is mature, with the population tending to be saturated. The crowding effect caused by excessive population agglomeration dominates, significantly reducing carbon productivity. The urbanization in the western region is still in the development stage, and the negative effects of population agglomeration are initially emerging, but the intensity is weaker than that in the eastern region. The central region is in a transitional stage of development, where the efficiency improvement brought by population agglomeration balances with environmental pressure, ultimately showing no significant impact.

From the perspective of land urbanization , this variable exhibits the most pronounced regional heterogeneity. The coefficients for the eastern and central regions are both negative and insignificant, while the coefficient for the western region reaches 143.6696, which is highly significant at the 1% level. Urban construction land in the eastern region tends to be saturated, making it difficult for continued extensive expansion to generate positive value; in the central region, the pros and cons of land development are intertwined, with positive and negative effects offsetting each other; in the western region, land resources are abundant, and moderate expansion of urban land use can optimize factor allocation, undertake industrial transfer, and fully release green benefits. This is also the core reason why land urbanization is not significant in the full sample: the effects of the east and west are opposite, and the overall average effect is offset.

From the perspective of industrial urbanization , the coefficients for both the eastern and central regions are not significant, while the coefficient for the western region is 4.3190, which is significantly positive at the 10% level. The proportion of non-agricultural industries in the eastern region is already at a high level, and the marginal green dividends from further optimizing the industrial structure are gradually diminishing. The industrial transformation in the central region is steadily progressing, but the low-carbon benefits have not yet been fully evident. The western region has considerable room for improvement in industrial urbanization, and the substitution of non-agricultural industries for traditional industries has achieved significant results, effectively driving carbon productivity.

In terms of control variables, the energy consumption structure is significantly negative in all three major regions, indicating that reducing coal dependence and optimizing the energy structure are common approaches to enhancing carbon productivity nationwide. The level of economic development is significantly positive in the eastern and central regions, but not significant in the western region, reflecting the supportive role of economic development in low-carbon transformation, which relies on the region's own economic foundation and technological conditions.

In summary, three-dimensional urbanization exhibits strong regional heterogeneity in carbon productivity, and the research hypothesis H2 is fully validated. This indicates that a uniform national development model is difficult to adapt to the realities of various regions, providing ample empirical evidence for the implementation of differentiated policies.

5.4. Endogeneity Test

There exists bidirectional causality and endogeneity between urbanization and carbon productivity: on the one hand, urbanization development alters regional energy consumption and carbon emission levels; on the other hand, carbon emission reduction constraints policies inversely adjust population settlement, land supply, and industrial layout. To mitigate the estimation bias caused by reverse causality, this paper re-performs a two-way fixed effects regression with all explanatory variables lagged by one period. The lagged independent variables are only influenced by past economic conditions and cannot be inversely affected by current carbon productivity, effectively avoiding bidirectional causality bias. The regression results show that lagged population urbanization and industrial urbanization significantly

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inhibit and enhance carbon productivity at the 10% statistical level, respectively; energy structure and per capita economic development level remain significant at the 5% and 1% levels, respectively, while land urbanization at the national level still has no significant average effect. The coefficient signs, significance, and benchmark regression of the core variables in the lagged regression are completely consistent with those in the benchmark regression, with only minor changes in coefficient magnitude, proving that the core relationship obtained in this paper’s benchmark regression is not disturbed by bidirectional causality endogeneity, and the causal inference conclusion is robust and reliable.

5.5. Robustness Test

To further verify the stability of the empirical conclusions, this paper conducts robustness checks from two perspectives: sample selection and time dimension. All models maintain the same variable, fixed effect, and clustered standard error settings as the baseline regression. The test results are presented in Table 6.

The four municipalities of Beijing, Shanghai, Tianjin, and Chongqing exhibit significant differences from ordinary provinces in terms of administrative level, economic structure, urbanization model, and low-carbon policies. To avoid interference from these special samples on the empirical results, this paper excludes the four municipalities and conducts regression analysis again. The results indicate that, after excluding the special samples, the coefficient signs and significance of each variable are highly consistent with the baseline regression, suggesting that the core research conclusions of this paper are not influenced by the municipality samples and are equally applicable within the scope of ordinary provinces across the country.

Table 6. Robustness Test Results

Variable	y		
	Excluding municipalities	2010-2015	2016-2022
x_1	-13.8925*	-6.7793**	-9.7335
	(0.0870)	(0.0190)	(0.3990)
x_2	-11.3256	11.6814	-5.9392
	(0.4580)	(0.3940)	(0.7040)
x_3	3.9875*	1.3925	3.1643
	(0.0670)	(0.3050)	(0.1120)
x_4	-0.2865**	-0.6032***	-0.1782**
	(0.0160)	(0.0020)	(0.0320)
x_5	2.3587***	0.5812**	1.4182
	(0.0100)	(0.0120)	(0.1870)
_cons	-19.5876***	-2.8039	-11.2181
	(0.0020)	(0.2680)	(0.1370)
N	338	180	210
R^2	0.6682	0.7454	0.4653

The year 2015 marks an important policy turning point, as China ushered in the transition from the "Twelfth Five-Year Plan" to the "Thirteenth Five-Year Plan", coupled with the official signing of the Paris Agreement. Consequently, the overall policy environment for urbanization and low-carbon development in China has undergone significant changes. Therefore, this paper divides the research sample into two periods: 2010-2015 and 2016-2022, with 2015 as the dividing line, for separate regression analysis. The results indicate that during the period 2010-2015, population urbanization, energy structure, and economic development level all exhibited

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significant effects, and the regression results are consistent with the logic of the benchmark model. In the period 2016-2022, only the energy consumption structure remained significant, while the significance of other urbanization-related variables weakened, but the direction of impact of all variables remained unchanged. This characteristic reflects that after 2015, China's urbanization entered a transformation period, with the marginal effect of urbanization on carbon productivity gradually declining, while the core logic of the two remained stable.

Based on the results of two robustness tests, the conclusions related to the benchmark regression and regional heterogeneity in this paper are not affected by special samples or policy periods, indicating that the empirical results are robust and reliable.

6. Conclusion and Suggestions

This paper utilizes balanced panel data from 30 provincial administrative regions in China from 2010 to 2022, employs a two-way fixed effects model combined with province clustering robust standard errors, and systematically explores the impact of urbanization on carbon productivity and regional heterogeneity from the dimensions of population, land, and industry. Endogeneity handling and robustness tests are conducted through methods such as lagging explanatory variables by one period, excluding special samples, and dividing policy periods. The study finds that population urbanization at the national level significantly inhibits carbon productivity due to agglomeration crowding effects, while industrial urbanization can continuously release green benefits through structural upgrading. However, the national average effect of land urbanization is not significant, primarily because of opposite directions and mutual offsets of positive and negative effects in different regions. Sub-regional results show strong spatial differentiation in the green effects of urbanization, with population urbanization in the eastern region having a prominent negative impact, land urbanization and industrial urbanization in the western region both exhibiting significant positive effects, and various urbanization indicators in the central region offsetting each other and showing no statistical significance. The energy consumption structure significantly inhibits carbon productivity nationwide. After dividing the sample based on the policy node in 2015, it is evident that the marginal impact of urbanization on carbon productivity gradually weakens as the development stage progresses, reflecting the phased characteristics of urbanization development shifting from scale expansion to quality transformation. After mitigating bidirectional causal endogeneity and excluding special samples from the four municipalities, the coefficient signs and significance of core variables have not undergone substantial changes, proving that the empirical conclusions of this paper are objective, reliable, and possess good endogeneity resistance and robustness.

Based on the above research conclusions, this paper proposes the following suggestions:

(1) In the eastern region, focus should be placed on intensive development and green upgrading to mitigate the negative effects of urbanization. Faced with the realistic background of population saturation, land scarcity, and prominent pressure on energy consumption, it is necessary to optimize the development model: reasonably regulate the scale of population agglomeration to avoid the congestion pressure brought by excessive urbanization, and promote the construction of intensive cities relying on a well-established public transportation system, thereby reducing carbon emissions from living and commuting; at the same time, strictly control the extensive expansion of cities, compress inefficient land use, accelerate the green transformation and upgrading of high-energy-consuming industries such as steel and chemical industries, and strengthen corporate emission reduction constraints through the carbon trading market mechanism. In addition, it is necessary to simultaneously optimize the energy structure, vigorously develop clean and low-carbon industries such as wind power and photovoltaics, with technological innovation and industrial upgrading as the core, weaken the

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inhibitory effect of population and land urbanization on low-carbon development, and continuously improve regional carbon productivity.

(2) In the central region, it is necessary to leverage the advantages of industrial transformation to foster a pattern of green and coordinated development. The low-carbon dividends from industrial upgrading should be fully harnessed, and the synergistic mechanism between industrial upgrading and energy transformation should be established by utilizing the geographical advantages and industrial foundation. Efforts should be made to accelerate the cultivation of emerging industries such as energy conservation, environmental protection, and green manufacturing, improve the regional industrial chain system, and promote the transformation of the industrial structure towards low-carbon and high-end development. At the same time, relying on regional scientific research resources, a collaborative platform for industry-university-research cooperation should be established, focusing on key areas such as energy-saving technologies and energy optimization for technological breakthroughs. Industrial energy conservation and urban-rural energy transformation should be simultaneously promoted to improve the energy utilization system. By doing so, the nonlinear positive benefits of industrial urbanization can be fully leveraged, consolidating the driving role of industrial upgrading in carbon productivity, and ultimately transforming the central region into a hub for regional low-carbon development.

(3) In the western region, it is necessary to rely on ecological endowments to balance land development and green development. Based on the abundant land resources and prominent ecological advantages, we should reasonably control the pace of development, adhere to orderly and moderate spatial expansion, and rely on the optimal allocation of land factors to stimulate the potential for green development. Specifically, it is necessary to fully utilize the clean energy resources in the west, scale up the deployment of new energy projects such as wind power and photovoltaics, and improve the cross-regional energy transmission system to transform resource advantages into low-carbon advantages. It is also necessary to actively explore the mechanism for transforming ecological value, develop models such as carbon sink economy and ecological compensation, and strengthen the synergy between ecological protection and green development. In addition, relying on the cooperation mechanism between the eastern and western regions, we should introduce advanced low-carbon technologies and development experience, make up for industrial and technological shortcomings, avoid the risks of extensive development, and thus form an urbanization development model that prioritizes ecology.

(4) At the national level, it is necessary to improve the cross-regional collaboration mechanism and establish a differentiated development system. We should coordinate the new urbanization and the dual-carbon strategy, abandon the homogenization model, and construct a coordinated development pattern of "quality improvement in the east, transformation in the middle, and ecological development in the west". To achieve this, it is necessary to improve the institutional systems such as cross-regional ecological compensation, green technology sharing, and low-carbon resource circulation, and build a unified environmental supervision and green development platform. At the same time, we should increase support for green industries and low-carbon projects in the central and western regions to narrow the gap in regional low-carbon development. Through these measures, we can fully unleash the green potential of urbanization in different regions and promote the coordinated development of high-quality and low-carbon urbanization in China as a whole.

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