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Exploring the Coupling of Land Development Intensity and Green Economy Development in the Pearl River Delta: Patterns, Challenges, and Strategic Pathways

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Abstract: This study investigates the spatiotemporal patterns of land development intensity and green economy development at the district and county level in nine cities within the Pearl River Delta (PRD). A comprehensive evaluation framework is developed using a coupling coordination degree model and panel vector autoregression (PVAR) model to explore the spatial and temporal evolution of their relationship. The research reveals several key findings. (1) In 2013–2023, land development intensity followed a pattern of "concentration in the east and south, and sparsity in the west and north", highlighting significant regional imbalances. (2) In 2013–2023, high-intensity development areas tended to cluster together, forming high-value zones, while low-intensity areas were often located next to similarly underdeveloped regions, reflecting a "low-value connection" trend. (3) There is a long-term stable co-integration relationship between land development intensity and green economy development. This study fills a gap in research at the district and county scale and offers practical insights for optimizing regional growth strategies and fostering green economic development across different areas in 2013–2023. These findings contribute to the design of balanced and sustainable development policies in the PRD, addressing both economic growth and environmental sustainability.

Keywords: land development intensity; green economy development; coupling coordination degree model; PVAR model; regional coordinated development

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Academic Editor: Bindong Sun

Received: 5 December 2024
Revised: 27 December 2024
Accepted: 3 January 2025
Published: 7 January 2025

Citation: Huang, H.; Xu, S.; Fang, K. Exploring the Coupling of Land Development Intensity and Green Economy Development in the Pearl River Delta: Patterns, Challenges, and Strategic Pathways. *Land* **2025**, *14*, 105. https://doi.org/10.3390/land14010105

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1. Introduction

Green economy development (GED) emphasizes sustainable economic growth by prioritizing environmental protection, resource efficiency, and low-carbon technologies. This approach is essential for addressing climate change and achieving the United Nations Sustainable Development Goals (SDGs), particularly those related to climate action (SDG 13), affordable and clean energy (SDG 7), and sustainable cities and communities (SDG 11) [1,2]. The green economy (GE) is conceptualized differently in international and domestic contexts. Globally, the GE underscores harmony between economic growth and environmental sustainability, aligning with SDG 8's goal of inclusive and sustainable economic growth. GED narrows the content of the GE in China, and it focuses on urban transformation, governance, and aesthetics enhancement, particularly within urban clusters. This study prioritizes the domestic context to address the unique socio-economic dynamics of the Pearl River Delta (PRD), aligning with national strategic goals while maintaining relevance to global sustainability targets [3,4]. Land development intensity (LDI) refers to the extent of land use and urban expansion, while green economy development (GED) focuses on

promoting sustainable growth through environmentally friendly practices. The integration of these two elements ensures that land development contributes to economic growth without compromising ecological health [3]. Although the PRD region is a leader in China's economic development, it still faces significant imbalances and regional disparities [4–6].

The PRD region, a leading economic hub in China, exemplifies both remarkable growth and stark regional disparities. Shenzhen, located in the eastern PRD, reported a GDP of USD 490 billion in 2022, reflecting its robust economic strength and advanced infrastructure. In contrast, Zhuhai and Zhongshan, situated in the western PRD, reported significantly lower GDPs of USD 61 billion and USD 54 billion, respectively [7–11]. These figures illustrate the uneven economic development across the region.

The PRD's strategic coastal position historically positioned it as a key node in maritime trade through the Maritime Silk Road. However, this legacy of connectivity and growth has not translated into equitable development [12]. While cities in the east benefit from higher levels of investment and infrastructure, western cities face challenges such as limited resource allocation, slower economic growth, and lagging human development indices [13]. Beyond GDP, disparities in income, education, and access to public services further expose systemic issues of unregulated development, fragmented governance, and inadequate regional planning.

These imbalances underscore the urgent need for a GED framework that fosters sustainable and equitable growth. Such a framework must prioritize regional coordination to bridge development gaps, equitable resource distribution to empower underdeveloped areas, and sustainable practices to align growth with environmental goals. Without addressing these systemic challenges, the PRD risks deepening regional divides, undermining its long-term economic resilience and compromising its global competitiveness.

LDI and GED are critical components of sustainable urban development. LDI measures the extent of land use and urban expansion and serves as an indicator of socio-economic development [14–16]. Narrowly, it focuses on the ratio of built-up land area to the total area, reflecting land utilization patterns [17–19]. Broadly, it encompasses economic, demographic, land, energy, and environmental factors, offering a comprehensive assessment of human impact on regional systems. The integration of LDI and GED ensures that land development contributes to economic growth without compromising ecological health [5].

Current studies on the interaction between LDI and economic growth primarily examine coupling and coordination mechanisms, often limited to land-use resources [20]. However, these studies frequently overlook other critical resources, such as forests, farmland, and green spaces, and neglect the role of carbon emissions in providing a holistic view of urban transportation and industrial development levels [21–24]. Moreover, the majority of research focuses on city-level dynamics, rarely extending to district or county scales, thereby failing to capture regional differences. This oversight is particularly significant in the PRD, where the relationship between LDI and GED is complex and pivotal to sustainable development.

To address these gaps, this study constructs a composite "LDI-GED" system for the PRD and employs a coupling coordination degree model and PVAR model to analyze the spatiotemporal evolution of their coordinated relationship. By focusing on district and county scales, this research provides a more granular understanding of regional disparities. The findings contribute to optimizing resource allocation, enhancing regional competitiveness, and fostering GED through coordinated mechanisms. Furthermore, this study offers insights into effective strategies for cross-regional collaboration and benefit-sharing, supporting both national and global sustainability goals. This study aimed to first, develop an evaluation framework using the coupling coordination degree (CCD) and panel vector autoregression (PVAR) model to analyze the spatiotemporal relationship between

LDI and GED in the PRD from 2013 to 2023; second, identify regional imbalances and clustering trends; and third, explore their long-term relationship to inform sustainable development policies.

The structure of the paper is organized as follows. The Section 2 provides an explanation of the theoretical background, framework, and index system. The Section 3 outlines the research design, detailing the methods and approach used. The Section 4 presents the results, showcasing the findings from this study. The Section 5 displays the discussion about the reason behind the results. Finally, the conclusion synthesizes the key insights, highlights the implications, and suggests areas for future research.

2. Theoretical Framework and Related Literature

2.1. Literature Review

The relationship between LDI and GED is a dynamic and mutually reinforcing interplay, with each influencing and supporting the other. On one hand, LDI, guided by principles of ecological civilization, lays the foundation for GED by ensuring the efficient and sustainable utilization of construction land, which provides the spatial framework necessary for fostering green economic initiatives. Compact and efficient land use can reduce carbon footprints, support green industries, and drive high-quality economic growth. On the other hand, GED, as a measure of economic green transition, offers essential financial resources and technological innovations to steer LDI toward more sustainable and eco-friendly directions, such as renewable energy projects and smart urban planning. This dynamic relationship forms feedback loops, where effective land use fosters GED, which in turn strengthens sustainable land development, creating opportunities for synergistic effects, like reduced environmental impacts and enhanced resource efficiency. However, challenges such as balancing development with conservation, addressing regional disparities, and mitigating the environmental consequences of rapid urbanization highlight the need for integrated policies, green technologies, and governance innovations. Adopting frameworks that align LDI and GED, such as promoting transit-oriented development, leveraging GIS technologies, and fostering cross-sector collaboration, can optimize land use while accelerating green economic transformation. Ultimately, the coupled relationship between LDI and GED underscores the importance of a holistic approach that integrates spatial planning with ecological and economic sustainability to achieve a virtuous cycle of development (See Figure 1).

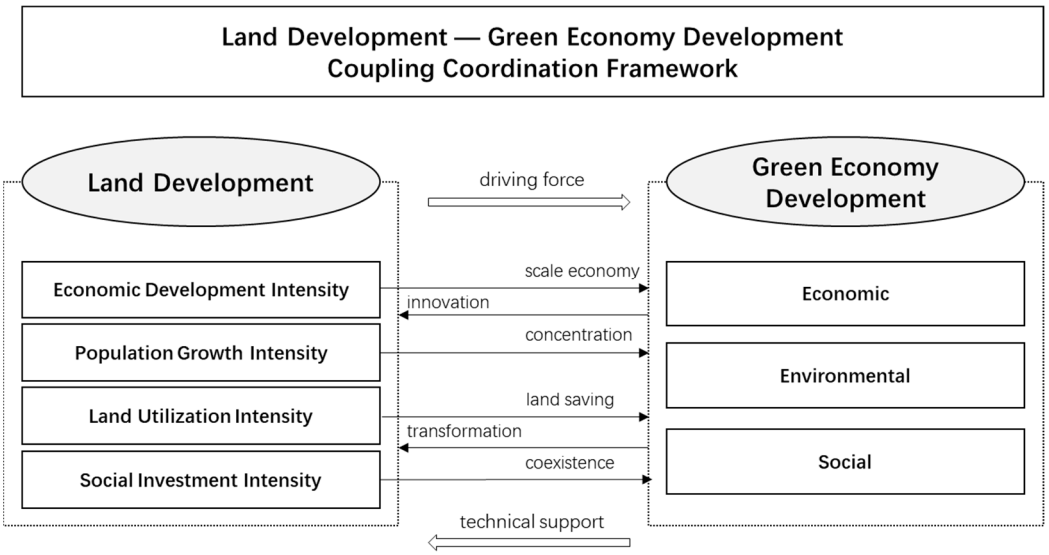


Figure 1. Research framework (drawn by the authors).

LDI significantly influences GED through its impact on spatial development, economic transformation, and environmental sustainability [23–25]. LDI facilitates resource aggregation, promoting economies of scale that drive productivity and green innovation, but balancing growth with sustainability is crucial to avoid resource depletion and ecological damage [26,27]. Spatial development also intensifies population concentration, improving infrastructure and public services, yet challenges, such as congestion and inequality, must be addressed to align with GED goals [28]. LDI promotes land use efficiency, shifting from expansive development to intensive use, particularly through the repurposing of underutilized land, like brownfields [29]. Social investment in green infrastructure further supports GED but requires strong public–private partnerships and regulatory support [30].

However, unchecked LDI can lead to urban sprawl, resource depletion, and environmental degradation. Regional disparities in development capacities call for tailored strategies to ensure equitable green transitions [23,24]. Effective integration of ecological considerations into land policies and the fostering of green technology innovation are essential for a sustainable future. GED reshapes LDI by steering it towards sustainable, efficient, and environmentally conscious practices, but challenges in balancing economic growth, environmental sustainability, and social equity persist [31,32]. GED mitigates the environmental risks of conventional LDI by encouraging technological innovations and policy interventions, like carbon neutrality [33]. Yet, systemic barriers, such as limited governance and financial constraints, hinder effective implementation, especially in less-developed regions.

Technological advancements enable industries to reduce pollution and increase efficiency, while emerging green industries require land for development [34–36]. The shift to green production may create conflicts over land use, particularly between ecological preservation, agriculture, and urban expansion. Comprehensive planning is needed to resolve these conflicts, but without addressing issues like speculative land use and unequal resource distribution, GED's full potential remains constrained.

In summary, while GED offers a promising solution to mitigate the negative impacts of conventional LDI, overcoming systemic challenges and ensuring equitable benefits require holistic governance and effective policy frameworks.

2.2. Theoretical Framework

In analyzing the spatiotemporal evolution of LDI and GED, this study utilizes the Major Functional Zoning Planning (MFZP) framework, which divides regions into differentiated functional zones based on their specific developmental priorities. For this research, the focus is on counties within the PRD region. By applying this zoning approach, this study explores the multi-scale factors influencing LDI, providing insight into how land development practices either contribute to or hinder sustainable growth. In the PRD, MFZP helps to illuminate regional disparities in economic development and environmental conservation, offering a solid foundation for integrating GE practices, particularly in areas with high LDI [37].

LDI serves as a driving force behind GED, with its four dimensions—economic development intensity, population growth intensity, land utilization intensity, and social investment intensity—significantly influencing the sustainability and effectiveness of GED strategies. Economic development intensity reflects the scale of economic activities and resource consumption, often leading to environmental degradation if not managed carefully. Population growth intensity, while essential for urban growth, exacerbates pressures on resources, infrastructure, and environmental quality, creating a delicate balance between development and sustainability. Land utilization intensity further complicates the relationship, as excessive land conversion can result in urban sprawl and the loss of green spaces,

undermining efforts to foster low-carbon development and green production. Social investment intensity is critical in mitigating these challenges, as robust investments in public services and community development are necessary to ensure that growth benefits society equitably and sustainably. GED, with its focus on low-carbon development and green production, aims to counteract the negative environmental impacts of LDI by promoting strategies such as renewable energy adoption, energy efficiency, and sustainable production practices. However, the interplay between high LDI and the achievement of GED goals is complex and fraught with tension, as unrestrained land development can hinder efforts to reduce carbon emissions and foster green industries. Effective management of LDI dimensions is thus essential for aligning land development with the objectives of low-carbon and green production, ensuring that urban growth contributes to, rather than detracts from, sustainable economic development (see Figure 1).

2.3. Index System

LDI is intrinsically linked to human activities and the intensity of land uses, as these directly, secondarily, and cumulatively impact urbanization [38]. The key factors that drive urbanization are economic development, societal dynamics, and land-use efficiency, which collectively shape the region's land-use patterns and urban growth [39]. Urbanization rates, population density, and migration trends reflect population aggregation dynamics and reveal how demographic shifts influence land development requirements [40]. These factors are particularly critical in the context of the PRD, where rapid urbanization has led to significant pressure on both land and resources, highlighting the need for balanced and efficient land use. Land utilization efficiency, which can be measured by economic output per hectare and its associated environmental impacts, assesses the effectiveness of land use in achieving sustainable economic growth [22]. This metric serves as a crucial gauge for urban planners, especially in the face of challenges such as environmental degradation, loss of agricultural land, and increased carbon emissions due to inefficient land use practices [39]. Furthermore, social investment strength, reflected in investments in infrastructure, education, and renewable energy, is a key indicator of a region's commitment to sustainable and inclusive growth [41]. The integration of these dimensions—economic, social, and environmental—through normalized data and weight assignments allows for a more nuanced evaluation of LDI, helping to identify regional imbalances, highlight areas of concern, and inform policies that promote coordinated, sustainable growth. This approach not only assesses the current state but also predicts future trends, guiding decision making towards mitigating the negative impacts of unchecked urbanization while fostering more resilient and balanced regional development.

Kasztelan (2017) highlighted the dual foundations of the GE by categorizing its factors into natural capital, representing environmental resources, and built capital, encompassing human-made infrastructure essential for sustainable development [42]. Canari (2017) proposed a transformative pathway for the GE through actionable steps, including valuing natural ecosystems, reducing inequality, greening economic sectors, reforming financial systems, and strengthening governance frameworks [43]. Loiseau et al. (2016) provided a critical evaluation of GE discourse by analyzing 877 documents and identifying 157 keywords, systematically categorizing them under the economic, environmental, and social pillars of sustainability [44]. GED, a focused subset of the GE, emphasizes low-emission strategies and closed-loop economies, offering a practical framework to address systemic challenges such as inequality, resource depletion, and climate change. This research quantified carbon emissions at the courtyard level to assess environmental impact. It highlights how localized activities, like composting and organic gardening, contribute to carbon reduction, offering insights for GED (see Figure 2). The GED framework operationalizes GE principles through

three interconnected dimensions—economic, social, and environmental—aiming to bridge the shortcomings of conventional economic models while promoting sustainable, equitable, and resilient development (see Table 1).

Table 1. Evaluation indicators for LDI and GED.

Target Layer	Factor Layer	Indicator Layer	Indicator Direction	Unit	Impact Coefficient
LDI	Economic Development Intensity	GDP density	+	CNY 10,000/m^2	0.1
		Industrial non-agriculturalization rate	+	%	0.1
	Population Growth Intensity	Population	+	10,000 persons	0.01
		Urban population proportion	+	%	0.05
	Land Utilization Intensity	Land cultivation index	+	%	0.14
		Proportion of built-up area	+	%	0.1
	Social Investment Intensity	Total electricity consumption	−	10,000 kWh	0.05
		Per capita green space	+	m^2	0.01
Green Economy Development	Economic	Per capita GDP	−	per capita GDP	0.005
		Foreign trade	+	USD 100 million	0.005
	Environment	CO_2 emission intensity	−	tons/billion CNY	0.1
		Industrial SO_2 emission intensity	−	tons/billion CNY	0.11
		Industrial smoke and dust emission intensity	−	tons/billion CNY	0.16
		Industrial wastewater emission intensity	−	tons/billion CNY	0.11
	Social	Average salary of employees	+	CNY	0.005
		Per capita disposable income of urban residents	+	CNY	0.005

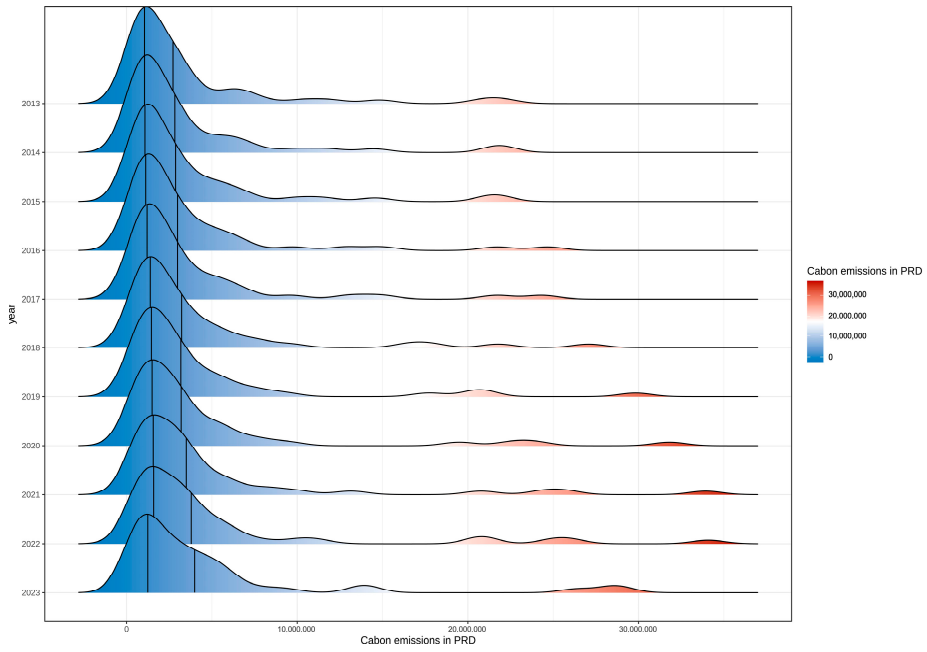


Figure 2. Carbon emissions in the PRD (drawn by the authors).

3. Methodology

3.1. Study Context

The Pearl River Delta (PRD), located in the south of China, is one of the most economically dynamic and densely populated regions in China, primarily within Guangdong Province. The PRD encompasses nine cities, including Guangzhou, Shenzhen, Dongguan, Zhuhai, and Foshan, and serves as a major economic and industrial hub. The region's strategic location along the South China Sea has made it a key center for trade, commerce, and manufacturing. It is particularly known for its thriving export-oriented industries, high-tech sectors, and rapid urbanization (see Figure 3).

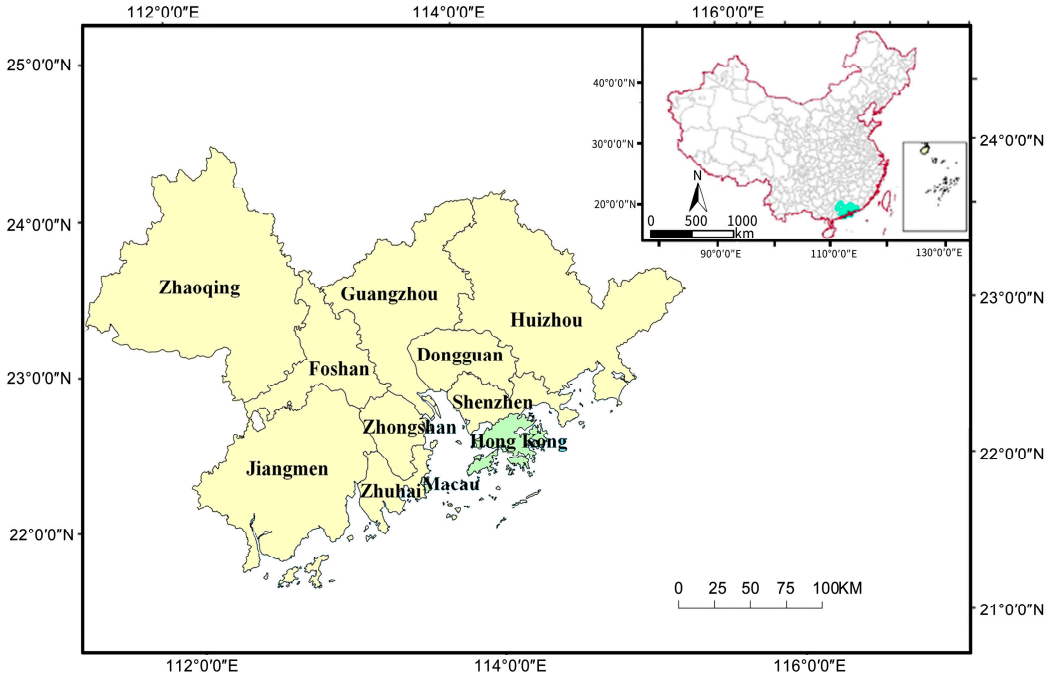


Figure 3. Location (the PRD is areas in yellow) (source: drawn by the authors).

3.2. Methods

3.2.1. Fuzzy Analytical Hierarchy Process (FAHP) and Linear Weighted Method

To effectively mitigate potential interference effects between different evaluation indicators, the first critical step is to implement a key data preprocessing procedure—the extreme value normalization method. This approach aims to normalize all evaluation indicators by adjusting their values to a uniform scale. It ensures fairness and accuracy in subsequent analyses and avoids unnecessary distortions or biases caused by differences in the magnitude or distribution characteristics of the indicators. The normalization formula is as follows:

$$x_{new} = \frac{x - x_{min}}{x_{max} - x_{min}} \quad (1)$$

where x_{min} represents the minimum value of the variable and x_{max} represents the maximum value of the variable. This process aligns the data for consistent comparison and analysis, providing a robust foundation for applying the FAHP and the linear weighted method.

In the evaluation of LDI and GED, we applied the Fuzzy Analytical Hierarchy Process (FAHP) to assign weights to two sets of indicators. This method integrates qualitative and quantitative approaches, constructing a multi-level model that decomposes the problem into objectives, criteria, and indicator layers. Subjective judgments are processed using fuzzy set theory, creating a fuzzy judgment matrix. This matrix undergoes consistency

testing and weight calculation. Finally, through defuzzification, clear weights are derived, providing a quantitative basis for strategy formulation.

The FAHP enhances the scientific rigor and accuracy of the evaluation, meeting the stringent standards required for academic research. The specific formula used in the FAHP is as follows:

$$S = \sum_{i=1}^{n} F_i W_i (i = 1, 2 \ldots n) \quad (2)$$

where S is the comprehensive cost considering multiple factors, F_i is the grid value, and W_i is the influencing factor.

3.2.2. Coupling Coordination Model

The coordination coupling degree is commonly used to reflect the strength of interactions between subsystems and is applied to describe the extent of mutual influence among multiple systems. It quantifies how well two or more systems interact and function together, offering insights into their interdependence and harmony.

The formula for calculating the coupling degree is as follows:

$$C = 2 \times \sqrt{\frac{U_1 \times U_2}{(U_1 + U_2)^2}} \quad (3)$$

where

C is the coordination coupling degree (range: 0 to 1);

U_1 is the evaluation function for System 1;

U_2 is the evaluation function for System 2;

C = 0 indicates no interaction or total decoupling between the systems;

C = 1 indicates maximum coupling, representing perfect interaction between the systems.

The coordination degree model reveals stark disparities across regions. High coordination areas (CCD > 8) have successfully integrated green technologies and sustainable practices, balancing economic growth with environmental sustainability. However, the scalability of this model to other regions remains uncertain, especially in areas with limited resources.

Moderate coordination areas (CCD 5–7) show some alignment between land development and the GE but remain in a transitional phase. These regions still rely heavily on traditional industries, raising concerns about the effectiveness of their green transition and the risk of superficial sustainability efforts.

Low coordination areas (CCD 1–4) are largely dependent on energy-intensive industries and show little integration of green practices. This continued reliance on outdated industrial models presents a significant barrier to sustainable development and highlights the need for targeted policies to shift these regions towards more sustainable growth.

Overall, the unequal distribution of GED across regions reflects the challenges of achieving comprehensive, region-wide sustainability. There is a clear need for more focused efforts to address the disparities between high and low coordination areas.

3.2.3. Panel Vector Autoregression (PVAR) Model

Based on the co-integration test and Granger causality test, the PVAR model reflects the interaction effect, impact degree, and contribution degree between the two systems, mainly through the impulse response function and variance decomposition function. The

advantage of the PVAR model is to exclude the limitations of endogenous and exogenous variables. With reference to Granger's causality test method, the model is built as follows:

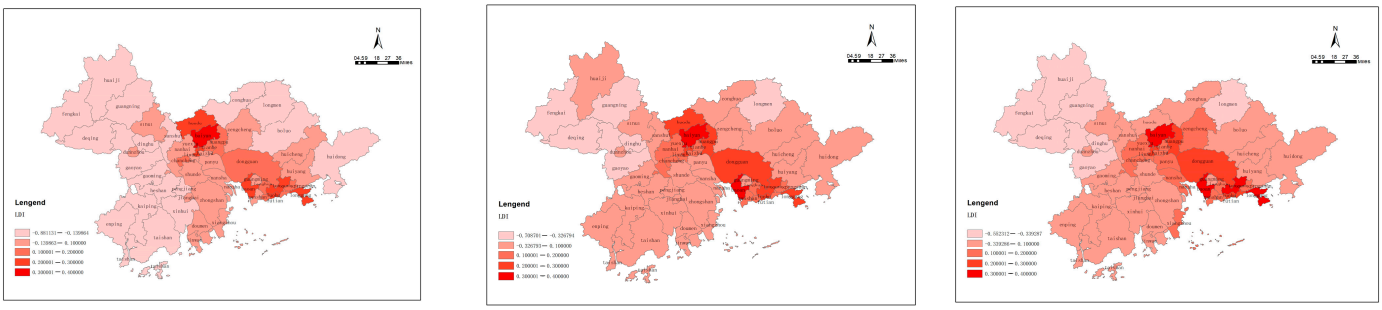
$$y_{it} = a_0 + \sum_{i=1}^{p} a_j y_{it} - p + \eta_i + \mu_t + \epsilon_{it} \quad (4)$$

where i and t are county units and time profiles; y_{it} and $_{i-p}$ represent the p of the y order lag term; a_0, a_j, and p represent section term, parameter matrix, and lag, respectively; and the number of periods η_i, μ_t, and ϵ_{it} represent the individual effect vector, time effect direction quantity, and random disturbance term.

4. Results

4.1. LDI Spatiotemporal Patterns

The spatial distribution of land development in the PRD revealed a stark imbalance, with a higher intensity concentrated in the east and south and relative sparsity in the west and north (Figure 4). From 2013 to 2023, peripheral areas experienced declining LDI, while coastal counties saw increases. High-intensity cores, such as Dongguan and Baoan, consistently exceed LDI thresholds, underscoring concentrated economic activity. Secondary areas, like Nansha and Jinwan, show moderate activity, while Guangzhou-Foshan forms a distinct, third-tier hub.



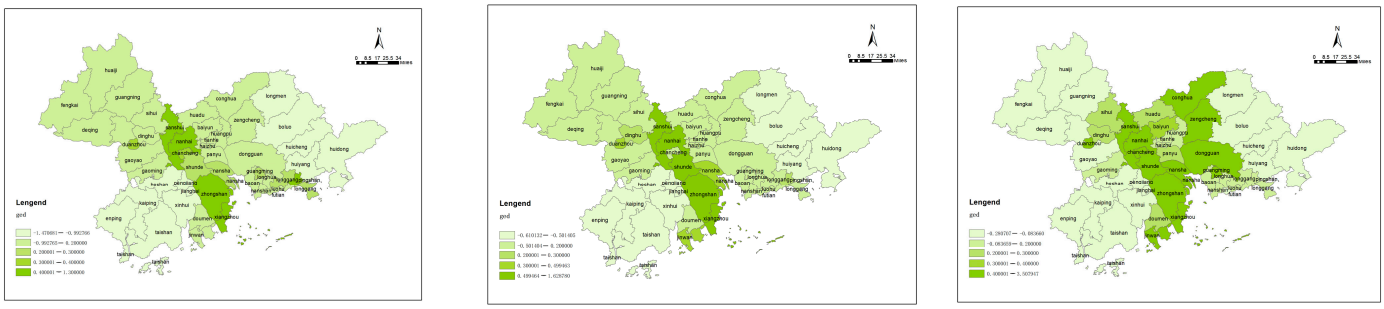
(**a**) (**b**) (**c**)

Figure 4. (**a**) LDI in 2013, (**b**) LDI in 2018, (**c**) LDI in 2023 (drawn by the authors).

Peripheral regions, like Zhaoqing, highlight severe internal disparities. In Zhaoqing, the eastern region, occupying 28% of the land, generates 70% of economic output, with an urbanization rate of 75.7%. By contrast, Huaiji County's per capita GDP was 2.41 times lower than Sihui's in the east, emphasizing uneven development. These imbalances demand targeted policies to ensure equitable regional growth while leveraging high-performing zones.

4.2. GED Spatiotemporal Patterns

From 2013 to 2023, the spatial dynamics of GED in the PRD shifted significantly. While the east coast initially dominated GED growth, by 2023, both eastern coastal cities and central areas displayed strong upward trends. The GED spatial pattern in the PRD revealed distinct clustering, where high-development zones formed "highland clusters" surrounded by similarly advanced areas, while low-development zones exhibited a "lowland connection" pattern, reinforcing disparities. This spatial dependency highlights underlying systemic mechanisms and offers insights for optimizing resource allocation and fostering balanced development (Figure 5).



(**a**) (**b**) (**c**)

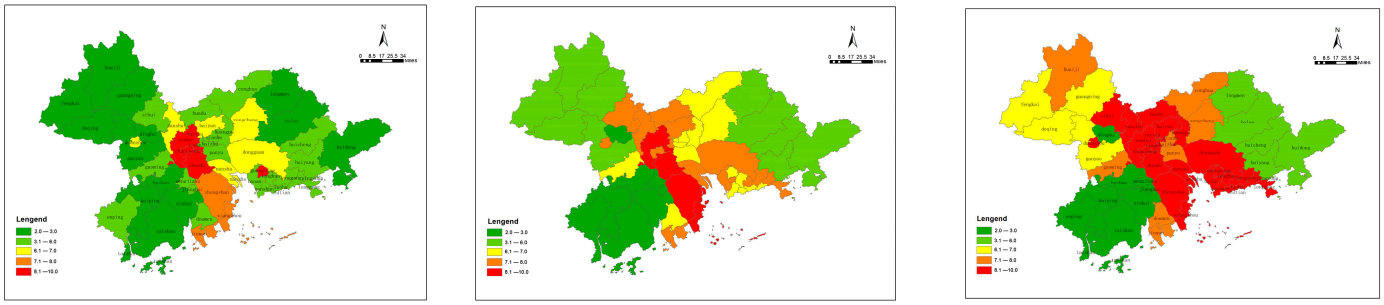
Figure 5. (**a**) GED in 2013, (**b**) GED in 2018, (**c**) GED in 2023 (drawn by the authors).

The GED landscape also underscored sharp intra-regional differentiation. Core areas such as Nanshan, Futian, Luohu, Yantian, Tianhe, Yuexiu, and Haizhu lead in GED due to low carbon emission intensity, averaging below 700 tons per billion CNY. These zones illustrated the positive synergy between economic activity and green growth. In contrast, second-tier areas, like Longhua, Pingshan, Chancheng, and Gaoming, though trailing the core, demonstrate moderate GED advancements, with emission intensity under 1000 tons per billion CNY.

However, the concentration of GED in core zones risks perpetuating spatial inequality. The "highland cluster" phenomenon amplifies resource and investment advantages in already-developed areas, while the "lowland connection" perpetuates stagnation in lagging regions. To mitigate these imbalances, a nuanced policy approach is essential—one that enhances low GED regions' capacity for carbon reduction, green innovation, and infrastructure development, while leveraging core zones as models for sustainable practices. This approach would address the dual challenge of promoting growth without exacerbating existing disparities, thereby advancing equitable regional sustainability.

4.3. CCD Spatiotemporal Characters

From 2013 to 2023, spatiotemporal patterns of land development and GE growth in the PRD displayed a clear "high in the center, low in the periphery" trend. Central regions, such as Yantian and Baoan in Shenzhen, Dapeng New District, Enping in Jiangmen, and Dongguan, exhibit strong alignment between economic development and green initiatives. These areas had successfully integrated green technologies and sustainable practices, but the challenge lay in maintaining this balance amid rapid growth (see Figure 6).



(**a**) (**b**) (**c**)

Figure 6. (**a**) CCD in 2013, (**b**) CCD in 2018, (**c**) CCD in 2023 (drawn by the authors).

In contrast, moderate coordination areas like Haizhu and Huangpu in Guangzhou, Guangming in Shenzhen, and Nanhai in Foshan showed emerging but less robust coordination between land development and green economy efforts. These areas were in a

transitional phase, moving toward more sustainable models but still relying heavily on traditional, resource-intensive industries.

Low coordination areas, such as Zhongshan, Taishan in Jiangmen, and Deqing in Zhaoqing, continue to lag behind, with limited integration of green economy practices. These regions remained dependent on outdated industrial sectors that hindered progress toward sustainability. The continued reliance on energy-intensive industries and poor environmental standards in these areas exacerbated the region's overall sustainability challenge.

These spatiotemporal patterns highlighted a key issue: uneven GED across the PRD. While some areas have made strides, many still struggle with outdated industrial practices. A more integrated, region-wide approach was needed to address these imbalances and accelerate the adoption of sustainable practices in less developed areas.

4.4. Interactive Effects of LDI and GED by the PVAR Model

4.4.1. Unit Root Test and Determining the Lag Order

In view of the limitation of heteroscedasticity in the original data, the unit root test methods of LLC, IPS, ADF-FISHER, and PP-FISHER in the PVAR model were selected to take the combined index of land development intensity and green economy development, and then the stationary test was carried out on the panel data processed through a logarithm to avoid the "pseudo-regression" caused by the non-stationary of the original data. To clarify whether there is a causal relationship and interaction between the two systems, as can be seen in Table 2, some data of the original series failed the stationarity test, that is, the comprehensive index of the GED test failed. Therefore, in the stationarity test, the first-order difference of the two ln-transformed variables is selected, and the result shows that $p < 0.001$ at the significance level of 1%, which significantly rejects the null hypothesis, indicating that there is a long-term stable co-integration relationship between LDI and GED.

Table 2. Panel unit root test.

Variable	LLC		IPS		ADF-FISHER		PP-FISHER	
	t	*p*	t	*p*	t	*p*	t	*p*
LDI	−12.9596	0.0000	−9.9384	0.0000	117.7564	0.1085	257.9642	0.0000
GED	24.5032	1.0000	17.7569	1.0000	8.2146	1.0000	18.6356	1.0000
lnLDI	−35.0817	0.0000	−6.9210	0.0000	190.3280	0.0000	157.7539	0.0002
lnGED	−1.0531	0.1462	−2.5774	0.0050	37.3294	1.0000	76.4149	0.9618
dlnLDI	−16.8042	0.0000	−10.6847	0.0000	309.4741	0.0000	727.3174	0.0000
dlnGED	−11.1406	0.0000	−9.4265	0.0000	170.8621	0.0000	521.6259	0.0000

In order to avoid reducing the accuracy of analysis results due to too short lag order and prevent too long lag order from affecting the integrity of the study sample size, Akaike Information Criteria (AIC), Bayes Criteria (BIC), and Han were selected as South Quine Information Criterion (HQIC) to determine the optimal lag order of the PVAR model. Among them, three information criteria select the minimum information value corresponding order, selected as the optimal lag order. According to Table 3, AIC, BIC, and HQIC are three information criteria, and six is taken as the optimal lag order, which once again confirms that there is a long-term equilibrium relationship between LDI and GED.

Table 3. Optimal lag order test of the PVAR model.

lag	AIC	BIC	HQIC
1	1.5599	2.59768	1.97087
2	1.61288	2.80333	2.08672
3	0.153062	1.53581	0.706439
4	0.226237	1.86019	0.883857
5	−1.57853	0.400459 *	−0.777664
6	−2.02786 *	0.460931	−1.01674 *

* indicates the lag order with the best (minimum) value.

4.4.2. The Granger Causality Test

To assess the robustness of the PVAR model results, we conducted Granger causality tests among the endogenous variables of this study (Table 4). When the hypothesis that GED is not the Granger cause of LDI is tested, the corresponding *p*-value is 0.000 (<1%), leading to the rejection of the hypothesis. Therefore, at the 1% significance level, it indicates that GED is the Granger cause of LDI. When the hypothesis that LDI is not the Granger cause of GED is tested, the corresponding *p*-value is 0.016 (<5%), leading to the rejection of the hypothesis. Therefore, at the 5% significance level, it indicates that LDI is the Granger cause of GED. This shows that LDI and GED have a bidirectional Granger causality relationship, meaning land development intensity and green economy development act as mutual forces driving each other's growth.

Table 4. Panel Granger causality test.

Equation	Excluded	chi2	df	Prob > chi2
dlnLDI	dlnGED	28.993	6	0.000
dlnLDI	ALL	28.993	6	0.000
dlnGED	dlnLDI	15.639	6	0.016
dlnGED	ALL	15.639	6	0.016

4.4.3. Impulse Response

To enhance the assessment of the dynamics of LDI and GED, we developed the impulse response function (IRF). Figure 6 illustrates the orthogonalized IRFs that describe the change in LDI as one standard deviation shock of GED. Based on a Monte Carlo simulation, the green and blue lines represent a 95% confidence interval. Figure 7a shows that GED is positively impacted by its own shock where the positive shock effect gradually weakens in the first period, strengthens in the second period, and then fluctuates and gradually stabilizes after the third period. Figure 7b shows that LDI exhibited a negative correlation with GED in the initial period, followed by a positive correlation that stabilized after the fourth period. Figure 6c shows that GED initially experiences a negative shock from LDI, and starting from the third period, a positive shock emerges and reaches its peak in the fifth period. After six periods of fluctuation, it tends to stabilize. Figure 7d shows that LDI experiences a positive shock, and the effect gradually diminishes, stabilizing after six periods of fluctuation. PRD's land development intensity and green economy development exhibit a significant self-reinforcing effect and mutual promotion effect.

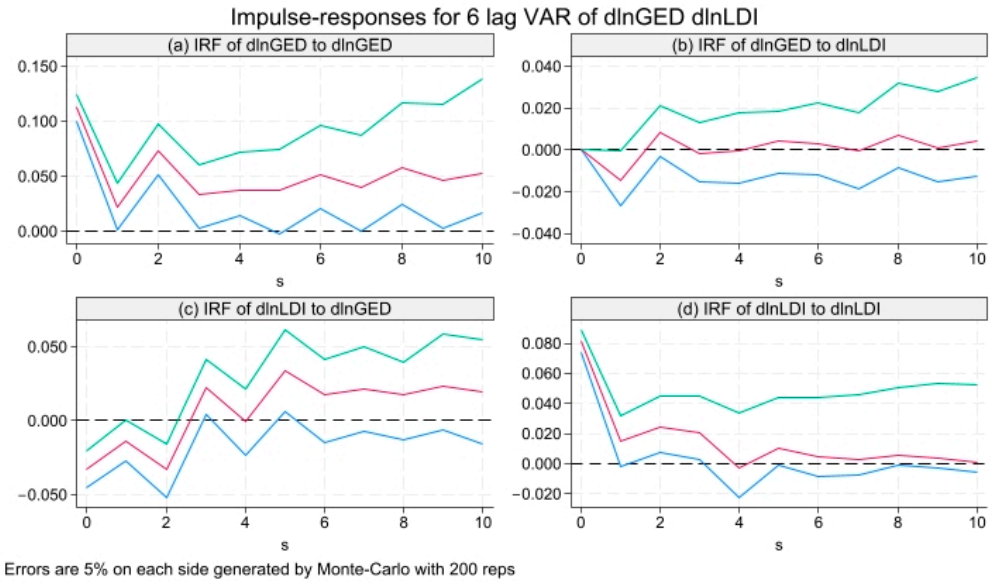


Figure 7. Impulse response function results (The red lines represent the estimated response, while the green and blue lines indicate the upper and lower bounds of the confidence interval, respectively.) (drawn by the authors).

4.4.4. Variance Decomposition

In order to delve deeper into the time-varying nature of the influence exerted by LDI and GED, we conducted forecasting error variance decompositions (FEVDs) of the endogenous variables (Table 5). The results show that in the first 10 periods, LDI's contribution to itself ranges from 0.643 to 1.000, indicating a large variance contribution that decreases at a relatively even pace. GED's contribution to itself ranges from 0.262 to 0.362 and stabilizes after the sixth period. GED's variance contribution to LDI ranges from 0.638 to 0.741 and reaches a relatively stable state in the sixth period with a slight upward trend. LDI's variance contribution to GED ranges from 0.000 to 0.355, showing a significant growth. The results of the FEVD and IRF analyses are congruent. Both LDI and GED exhibit substantial endogenous dynamics and mutual interdependence.

Table 5. Forecasting error variance decompositions.

s	LDI		GED	
	LDI	GED	LDI	GED
1	1.000	0.638	0.000	0.362
2	0.911	0.683	0.089	0.317
3	0.912	0.676	0.088	0.324
4	0.808	0.684	0.192	0.316
5	0.707	0.723	0.293	0.277
6	0.666	0.738	0.334	0.262
7	0.645	0.738	0.355	0.262
8	0.643	0.738	0.354	0.262
9	0.698	0.741	0.302	0.262
10	0.740	0.737	0.260	0.263

5. Discussion

The spatial differentiation observed in the PRD underscored the region's complex development landscape, where disparities in LDI and GE integration remained pronounced.

In high coordination areas, like Shenzhen's Yantian and Baoan districts, significant strides have been made in aligning land development with green economic principles, fostering growth without compromising environmental integrity. These areas illustrated how innovative green technologies and sustainable urban planning could drive economic performance while maintaining ecological sustainability [45]. However, the pattern in moderate coordination areas, such as Haizhu and Huangpu districts in Guangzhou, highlighted an ongoing struggle to balance industrial expansion and green transformation [46]. While these regions showed promising developments in integrating green sectors, their heavy reliance on traditional industries continued to undermine progress. This reliance posed a challenge in transitioning towards a GE, necessitating more deliberate investment in clean technologies and sustainable infrastructure to ensure long-term growth [47,48].

Conversely, low coordination areas, such as Zhongshan and Taishan, presented a more concerning scenario where the over-dependence on resource-extractive, energy-intensive industries exacerbated environmental degradation [49]. These regions faced considerable challenges in achieving a GE transition, which required not just technological upgrades but also an overhaul of the socio-economic structures that supported unsustainable industrial practices [50]. Without targeted policy intervention and restructuring efforts, these areas risked further entrenching regional inequalities, leading to a scenario where the benefits of GED were unevenly distributed. This was particularly concerning as low coordination areas were likely to remain laggards in the green transformation, further widening the socio-economic divide within the PRD.

The integration of LDI within China's MFZP model was essential in shaping the region's development. LDI helped optimize land use across urban, industrial, agricultural, and ecological zones, fostering green infrastructure and minimizing environmental impacts. High coordination areas, like Shenzhen, exemplified the potential of LDI in promoting sustainable urban development, while moderate and low coordination areas highlighted challenges related to land-use inefficiency and polluting industries.

This study called for a more holistic development strategy that integrated land-use planning, green economic initiatives, and social equity. Uneven development hindered regional sustainability and exacerbated environmental inequalities. Policies need to ensure inclusive growth, promoting green transformation in all regions, especially peripheral ones. Furthermore, top-down policies should be complemented by bottom-up engagement from local communities, industries, and stakeholders.

Moving forward, the PRD needs a regional development framework focused on sustainability, equity, and long-term growth, extending the low-carbon transition to all regions. Policymakers must incentivize green industrial transformation, foster innovation, and create sustainable urban spaces while addressing the challenges faced by less-developed districts. The success of these strategies depends on the ability to adapt policies to dynamic local, regional, and global forces. By doing so, the PRD could become a model for sustainable and equitable growth.

This study also emphasized the need to align domestic GED definitions with international frameworks, such as the United Nations Sustainable Development Goals (SDGs). Future research could explore how regional GED definitions interact with global sustainability standards and how these differences might influence broader policy frameworks.

6. Conclusions

The findings of this study revealed significant spatial differentiation in LDI and GED across the PRD. The region demonstrated a clear "high in the center, low in the periphery" trend, with high-intensity development areas, such as Shenzhen and Dongguan, exhibiting strong alignment between land development and GE growth. These areas exemplified

how urbanization and economic development could coexist with environmental sustainability [51]. In contrast, peripheral areas, like Zhongshan and Taishan, faced substantial challenges due to their reliance on energy-intensive industries, highlighting the need for more balanced and regionally coordinated policies that integrated economic growth with environmental sustainability [52].

The analysis categorized the PRD into three types of regions based on their coordination levels: high coordination areas, where land development and GED were well integrated; moderate coordination areas, where progress was evident but challenges remained; and low coordination areas, where restructuring was needed to move towards more sustainable industries. The uneven distribution of GED across the region presented both challenges and opportunities for future growth. The critical takeaway was the need for a more inclusive and regionally coordinated approach that promoted sustainability across all areas, ensuring that no region was left behind in the transition to a GE.

Overall, this study underscored the importance of adopting policies that addressed the spatial and socio-economic disparities within the PRD. A balanced, sustainable approach to regional development, coupled with the integration of green technologies, was essential for ensuring long-term economic growth that benefited all regions equally.

This study contributes to the understanding of sustainable urbanization by highlighting the need for regionally coordinated policies that balance economic growth with environmental sustainability, offering insights into regional planning for rapidly developing areas, like the PRD, on the county scale. However, it has several limitations, including reliance on aggregated regional data that may overlook local variations, a focus on current trends limiting predictive capacity, and a regional scope that may not fully generalize to other contexts. Additionally, the lack of qualitative data, such as stakeholder perspectives, restricts a more comprehensive understanding of socio-economic and institutional challenges. Addressing these limitations in future research through granular data analysis, broader comparative studies, and the integration of qualitative methods can further enrich the findings and enhance their applicability to global sustainable development initiatives.

Author Contributions: Conceptualization, H.H.; methodology, K.F.; validation, H.H., S.X. and K.F.; formal analysis, H.H., S.X. and K.F.; data curation, S.X. and K.F.; writing—original draft preparation, H.H., S.X. and K.F.; writing—review and editing, H.H., S.X. and K.F. visualization, S.X. and K.F.; supervision, H.H.; project administration, K.F.; funding acquisition, H.H. and K.F. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Guangdong Office of Philosophy and Social Science (Grant No. GD24XGL068) and Guangzhou Urban Planning and Design Co., Ltd. (Grant No. GZUPDC03).

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

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

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