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The Impacts of Urbanization on Carbon Emission Performance: New Evidence from the Yangtze River Delta Urban Agglomeration, China

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Abstract: Regarding the carbon emission performance of urbanization, the changes in carbon emissions and carbon sinks have attracted particular attention, while the internal impact mechanism has been under-researched. Conventionally, urbanization has either improved or hindered carbon performance. However, this is not always the case as the paths of urbanization affecting carbon emission performance are diverse. Hence, this paper proposes a theoretical framework to investigate how urbanization influences carbon emission performance, specifically the indirect effects of land development/land-use efficiency, by taking the Yangtze River Delta urban agglomeration, China, as a study case. Empirical results show that urbanization improves carbon emission performance due to the agglomeration effect. As an intermediary pathway, land-use change has a two-sided impact on carbon emission performance. Urbanization can both worsen and improve carbon emission performance through increasing land-development intensity and promoting land-use efficiency, respectively. However, the positive impact of land-use efficiency can alleviate the problem of increasing carbon emissions caused by land over-development. Hence, the integration of urban planning strategies with land use management policies can help to achieve sustainable urbanization.

Keywords: urbanization; carbon emission performance; impact mechanism; land-use change; Yangtze River Delta urban agglomeration

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1. Introduction

Rapid urbanization has led to changes in carbon emissions, and the resulting warming has attracted global attention [1]. Sustainable cities and communities (SDG11) and climate action (SDG13) have been identified as key goals for achieving sustainable development, highlighting the challenge of maintaining urban growth without increasing the burden on the climate. Researchers have comprehensively explored the carbon emission effects of urbanization, and found that it is facilitated by agglomeration of population to urban areas, extensive expansion of urban land scale [2], consumption of energy, and degradation of high-carbon sink ecosystems [3]. Such phenomena have greatly contributed to the surge in carbon emissions and the reduction of carbon sinks [4], which means that urbanization will hinder carbon emission performance (CP).

Opponents insist that such views only focus on the impact of negative externalities of agglomeration, while ignoring the positive role of scale economies in determining CP [5].

As if no matter how urbanization develops, the expansion of output scale will always lead to consumption of more and more energy while emitting more and more carbon dioxide, thereby aggravating climate warming. The literature on the new economic geography indicates that highly urbanized cities are those with prominent sharing mechanisms and knowledge spillovers [6]. It identifies the potential for technological innovation and productivity improvements and gives a firm edge for decoupling production from carbon emissions [7]. Intuitively, the positive externalities of the agglomeration effect will help to improve CP.

However, research progress in spatial and environmental justice capture the important role of land use in determining CP [8]. As an external manifestation of urbanization, land-use change directly affects the spatial distribution of population density, economic growth, and industrial structure, resulting in regional differences in carbon emissions [9]. If more and more land is developed into urban land, urbanization will hinder CP [10]. On the contrary, if urbanization can increase the land-use efficiency by optimizing the allocation of land resources, then CP is expected to be improved [11,12]. In addition, land-use change is related to the financial purpose of the city [13]. Specifically, cities with higher level of urbanization are always accompanied by higher land value [10]. Governments tend to allocate fiscal spending to the land market in order to obtain high returns in the short term [11,12], thus changing the land-development intensity (LD) and land-use efficiency (LE). This fact squeezes the investment and resource allocation in social innovation, and affects CP [13,14]. Hence, the impact of urbanization on CP is ambiguous [14], requiring diversified theoretical discussion and empirical experience. Exploring how urbanization alters CP would help governments and policymakers formulate targeted and fair carbon reduction strategies, as well as achieve the "win–win" between urbanization and carbon neutrality.

Yangtze River Delta urban agglomeration (YRD), China, is an ideal and typical area for studying the relationship between urban growth and environmental pollution. First, as the region with the fastest economic growth rate and the highest level of urbanization, YRD is experiencing rather significant agglomeration effects and land-use changes [2]. Second, the population scale in YRD is rather high and the land resource and energy consumption are expected to increase [15]. Hence, an urban development model in such a region usually places great expectations to provide regional experiences.

This paper aimed to explore how urbanization affects CP. The study proposes a multi-level theoretical framework to depict two channels where urbanization may affect CP. One follows traditional thinking and focuses on economies of scale and technological progress. The other focuses on indirect paths such as land-use change triggered by urbanization development, emphasizing the resource allocation. This paper found that the relationship between urbanization and CP largely depends on the change between positive externalities of economics and the negative externalities of ecological environment [16]. In fact, highly urbanized cities are those with a concentration of highly skilled talent, capital, and technology, and therefore have outstanding economies of scale together with technological progress [17]. In turn, the high density of population and homogeneous industries consume more energy and produce more CO_2. These findings complement the theoretical thinking on the relationship between the economic externalities and eco-environmental externalities of urbanization. From the perspective of indirect influence, as the mediators, LD can hinder CP through encroaching high-carbon sink ecosystems, squeezing innovation investment, and exacerbating resource misallocation. In contrast, LE can improve CP through improving resource allocation efficiency. And the positive impact of LE can alleviate the pressure of increasing carbon emissions caused by land over-development.

The likely contribution to the literature is twofold. First, this paper adds insights into the impact path of urbanization on CP by constructing a theoretical framework. Most of the existing studies on urbanization and CP are based on mathematical models, focusing on the determination and explanation of correlation coefficients, and the mechanism impact has often been overlooked, let alone the influence pathway.

Second, our findings also add insights into the environmental impacts of urbanization by highlighting the mediating role of land-use change. Through establishing indirect pathways, we capture the fact that a region's CP is determined by not only its inherent characteristics, but also its LD and LE, which may determine different development strategies for even the same region. Our empirical results show that land-use change is an indispensable facet to understand the carbon emission effect of urbanization.

The paper consists of six sections. Section 2 illustrates the influence mechanism and puts forward the theoretical hypothesis. Section 3 describes the study area, methodology, variable selection, and data. Section 4 presents the results. Sections 5 and 6 concern the discussion and conclusions, respectively.

2. Theoretical Context and Research Hypotheses

2.1. Theoretical Context

Urbanization can be understood as the process of spatial agglomeration and diffusion of socio-economic factors. Population urbanization is an important indicator for studying the interaction between urban growth and ecological environment, as it considers both carbon emission sources and the people affected by it [18]. Hence, this paper quantitatively calculated the level of urbanization (UL) from the perspective of population urbanization, which is measured by the percentage of the urban population in the total population

CP can be defined as an indicator to measure the effectiveness between inputs (i.e., labor, GDP, resources) and carbon dioxide emissions under the framework of production theory [19], which is the key to connecting the "dual carbon" goal and sustainable growth of cities. The climate crisis is ostensibly an environmental issue, but in essence it is a question of economic development models. An effective solution lies in exchanging the minimum environmental cost for the highest economic and social welfare returns, rather than focusing only on the scale and intensity of carbon emissions [20]. This paper used an input-output model to calculate CP, including desirable output and undesirable output.

Earlier research studies quantitatively evaluated the impact of UL on CP through econometric or mathematical models, which have naturally assumed that urbanization will inevitably lead to changes in regional CP [21]. Intuitively, massive land expansion, over-concentration of population, and economic activities will fail to improve CP, since it increases resource demand and energy consumption [22]. However, existing studies related to human well-being also capture the fact that the sharing of public infrastructure can help improve the efficiency of resource and energy use, thereby slowing the growth rate of carbon emissions [23]. Hence, there is controversy between the impact of urbanization on CP.

Recent studies have further revealed that the essence of the relationship between UL and CP is the interaction between agglomeration and environment [16]. Agglomeration promotes the formation of learning, matching, and sharing effects by concentrating the population, economic activities, and factors of production from one region to a specific region [24]. It encourages joint action and collective efficiency, resulting in savings on production costs, as well as increasing resource and energy efficiency, then contributing to CP. However, agglomeration does not always help to improve carbon emission performance. Instead, it often hinders CP by increasing energy consumption and carbon emissions per unit of production [25].

The literature on spatial and environmental justice studies has consistently emphasized the critical role of land-use change, and presents it as an intermediary between urban growth and environmental pollution as a result of rapid urbanization [19,20]. Specifically, LD and LE reflect the transformation direction of urban space and industrial structure and the coupling level of the urban system and land use system, respectively. Therefore, the impact of UL on CP depends on not only the trade-off between different types of agglomeration, but also the linkages between land-use change and economic, social, and ecological factors of its location, respectively. That is to say, urbanization will exhibit a different CP even in areas with the same or similar agglomeration effects due to differences in land-use change.

2.2. Research Hypotheses

Based on the above theoretical background, this paper constructed a theoretical framework that includes direct impact mechanisms and indirect impact paths (Figure 1).

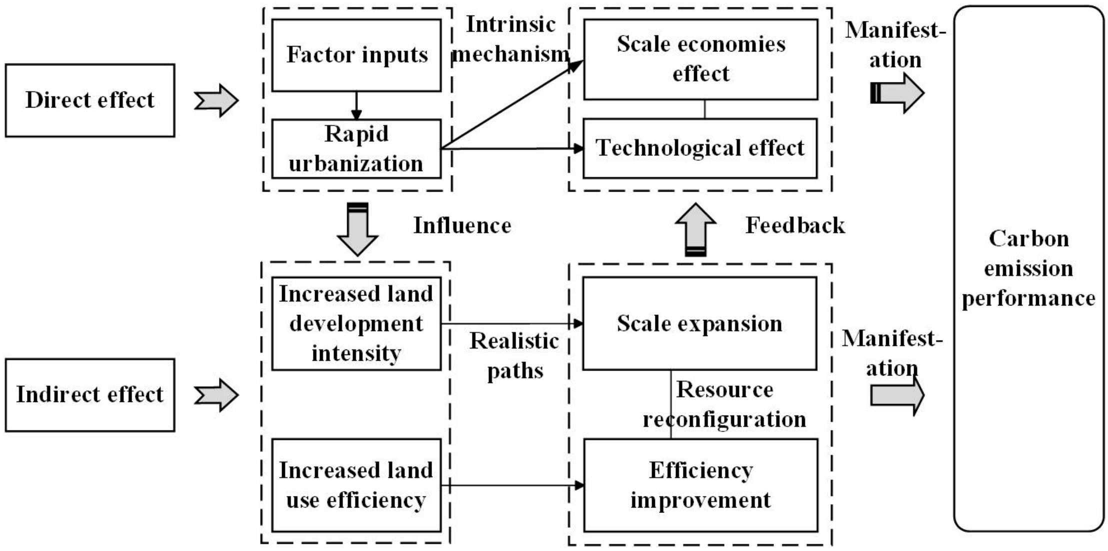

Figure 1. Theoretical framework.

2.2.1. Direct Mechanism: Scale Economies or Diseconomies

The ongoing debate about the relationship between UL and CP is related to the long-standing focus on the changes of positive or negative externalities of agglomeration in the new economic geography. Agglomeration refers to the phenomenon of relative spatial concentration of economic activities and industries. Increasing evidence has suggested that compared with decentralized modes of production, centralized modes of production have prominent economies of scale, increasing returns, and show technological progress [26].

Environmental economics usually regards energy consumption as the direct source of carbon emission, while energy and resources are essential inputs or intermediate products in the production process. In this context, urbanization has an impact on CP in at least three ways due to the sharing, matching, and learning mechanisms. First, the rapid development of urbanization has generated economies of scale and reduced energy and resource consumption, thus contributing to the improvement of CP [27]. Second, by connecting knowledge spillovers between different industries and sharing a more proficient labor market [28], rapidly urbanizing cities can generate new industries that replace or crowd out energy-intensive and polluting industries [29], thereby reducing negative environmental externalities. Third, the centralized production and living patterns enable the efficient use of resources and reduce energy consumption per unit area.

Although the agglomeration of population and industry has collectively contributed to the prosperity of urbanization, it is not a case of “ the more the better” [5]. When more and more people, enterprises, and production factors are concentrated in urban areas with a high level of urbanization, it will naturally increase the competition for limited resources and space, as well as the need of fossil fuels [30]. In other words, there are negative externalities of agglomeration, such as increased pollutant emission and degradation of the ecological environment. For example, Qiao et al., (2023) confirmed that excessive energy consumption in economically developed regions is the main cause of the deterioration of regional CP [31]. Hence, this paper proposes the first hypothesis as follows.

Hypothesis 1: *Urbanization has a direct impact on CP. The positive externalities can significantly improve the CP, while the negative externalities will hinder the improvement of CP.*

2.2.2. Indirect Mechanism: From Scale Expansion to Efficiency Improvement

Resource economics emphasizes that land use has become an important mediator of the influence of urbanization on CP under the strong demand of population growth and economic development. Intuitively, the higher the intensity of land development, the greater is the scale of conversion from non-construction land to construction land, which exacerbates the consumption of energy and resources, and thus changes the CP [31]. In addition, research related to environmental justice consistently shows that cities with higher LD are those with intensive economic activities, which can attract population inflows and industrial migration [32]. In this case, the agglomeration of people and the development of industries consumes a lot of energy and resources, leading to carbon emissions and pollutant emissions [33].

In addition, the research should not be limited to the impact of land-development intensity on the carrying capacity of resources and environment. Similar and related to the environmental justice literature, but rooted in urbanization and land-use change, are those research studies that assess the relationship among urbanization-land development-land values [34]. Specifically, land located in cities with higher urbanization will be more profitable [35,36]. Therefore, land-use change is often closely related to the fiscal revenue and expenditure of a region, especially the intensity and scale of the land development. Given that land finance can bring higher fiscal revenue in the short term, government will tend to allocate fiscal spending to the real estate market [37]. By reflecting the distribution of land and capital in the real estate market, the LD acts as an intermediate variable, and may reproduce the unequal development model of "land finance–real estate development" [38]. These facts will squeeze investment and resource allocation for innovation [39], which distort the allocation of resource elements and hinder the improvement of CP. Hence, this paper proposes the second hypothesis as follows.

Hypothesis 2: *Urbanization will inhibit CP through increasing LD.*

Land-use efficiency is another important manifestation of urbanization development, emphasizing the allocation of resources and the adjustment of land use structure. In general, land-use efficiency depends on population density and the intensity of economic activity. Under the background of limited supply of land resources, cities with higher levels of urbanization tend to have higher land-use efficiency [40].

There are at least three ways in which urbanization affects CP through LE. First, increasing in LE of one city is the result of the adjustment of its industrial structure and the agglomeration of economic activities. It suggests one city can "reinvent" itself through integrating industries and optimizing resource allocation [41]. In the process, collective efficiencies, and industrial symbiosis can gain greater access to the upgrade of production, as well as save on resource consumption costs, thus improving CP. Second, LE will reduce the expropriation of new land through optimizing land use structure and spatial allocation [16]. This process can not only effectively decrease the consumption of resources, but also the carbon emissions, thereby benefiting CP. From a dynamic perspective, LE will broaden the opportunities of achieving an agglomeration effect and scale effect, then allowing the decoupling of production from carbon emissions of one city [42]. Third, LE provides a better chance to regional resource reallocation by restructuring existing strengths, thereby decoupling production from resource consumption and pollution. Hence, this paper proposes the third hypothesis as follows.

Hypothesis 3: *Urbanization will improve CP through increasing LE.*

3. Research Design

3.1. Study Area

The YRD is located in East China, covering Shanghai, Zhejiang province, Jiangsu province, and Anhui province (Figure 2). The YRD is not only the region with the highest urban agglomeration and urban density in China, but also an important engine of economic development. In the face of the approaching time for carbon peaking and the realistic demand for promoting sustainable economic development, the "Outline of the Yangtze River Delta Regional Integration Development Plan" proposes to build a demonstration area for sustainable and high-quality development and improve the resource allocation capacity. Therefore, an in-depth exploration of the impact mechanism of urbanization on CP in the YRD can not only provide a scientific basis for the low-carbon development of the region, but also play a leading and exemplary role for the promotion of the "dual carbon" goals in other regions and cities across the country.

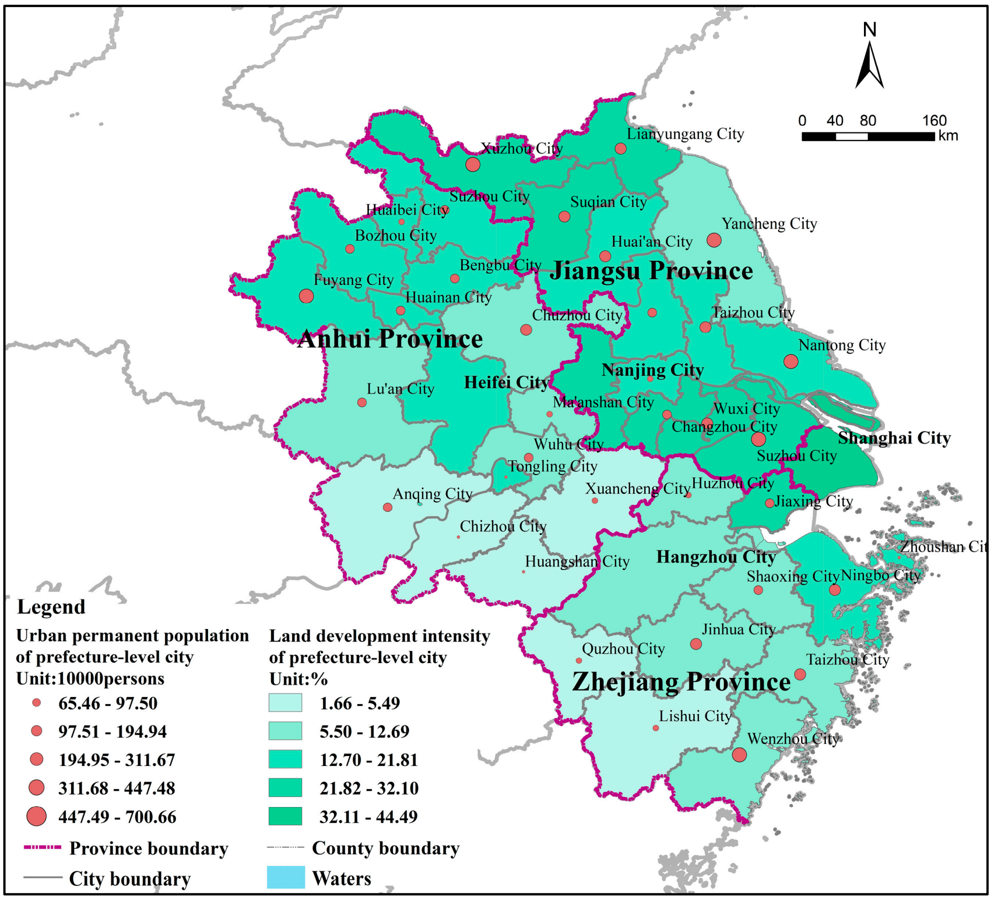

Figure 2. Study area.

3.2. Variable Specification

3.2.1. Proxy Variable for Carbon Emission Performance (CP)

In this paper, CP is used as a dependent variable, which is measured by the SBM model. The formulas are as follows [43]:

$$\rho^* = min \frac{\frac{1}{m}\sum_{i=1}^{m} \frac{\overline{x_i}}{x_{i0}}}{\frac{1}{S_1+S_2}\left(\sum_{r=1}^{S_1} \frac{\overline{y_r}^g}{y_{r0}^g} + \sum_{r=1}^{S_2} \frac{\overline{y_r}^b}{y_{r0}^b}\right)} \quad (1)$$

$$\text{s.t.}\begin{cases} \overline{x} \geq \sum_{j=1,\neq 0}^{n} \gamma_j x_j, \\ \overline{y}^g \geq \sum_{j=1,\neq 0}^{n} \gamma_j y_j^g, \\ \overline{y}^b \geq \sum_{j=1,\neq 0}^{n} \gamma_j y_j^b, \\ \overline{x} \geq x_0, \overline{y}^g \leq y_0^g, \overline{y}^b \geq y_0^b, \gamma \leq 0, \end{cases} \quad (2)$$

where ρ^* represents the CP; m, S_1, and S_2 are number of the inputs (x_i), desired outputs (y^g) and undesired outputs (y^b), respectively. $\overline{x}$, $\overline{y}^g$, and $\overline{y}^b$ are the corresponding relaxation variables. Table 1 shows the evaluation indicators of CP, which combine the existing studies.

Table 1. Input–output index system.

Variable Type	Measure Index	Representation and Unit
Input	Capital input	Investment stock of fixed assets (million Yuan)
	Labor input	Employed workers (million people)
	Energy consumption	Urban electricity consumption (million kw·h)
Desirable output	GDP	Annual real GDP (million Yuan)
	VCS	Vegetation carbon sequestration of (million tons)
Undesirable output	CO_2 emissions	Energy consumption CO_2 emissions (million tons)

3.2.2. Control Variables

Control variables can be divided into four sets. First, in response to the literature of agglomeration economies, this paper controls the economic development (ED) and population density (PD) as the proxy for the changing scale of urbanization [22,44]. They are simple indexes to indicate the agglomeration of economy and population at the local level, measured by GDP per capita and the ratio of total population to the total land area, respectively. Concentrated population distribution can generate scale economies, which can improve carbon performance. However, increasing population density means higher CO_2 emissions.

Second, this paper controls sector-specific characteristics. Industrial structure (IS) can capture the composition characteristics of urban production factors, measured by the share of secondary industrial added value to GDP. Specifically, the industrial sector tends to be more carbon emission-intensive than others in the ratio of road area to total land area. The optimization of the IS promotes the development of the city in a cleaner direction [45]. Road density (RD) reflects the convenience of urban transportation, measured by the ratio of road area to the total land area [46]. In the case of the same traffic volume, the higher the road density, the more convenient is the traffic, and the higher is the efficiency of the carbon emissions in motor vehicles—carbon dioxide from the combustion of motor vehicle fuels has been shown to be the main cause of the increase in urban CO_2 emissions.

Third, this paper controls the factors related to policy, such as environmental regulation (ER) and foreign indirect investment (FDI). Specifically, ER can significantly improve CP by imposing environmental constraints to "fine wash" enterprises and industries, which is measured by the ratio of environmental investment to fixed investment [47]. Cities with higher FDI tend to attract more "green" production activities from foreign companies with leading innovative technologies. However, the entry of FDI may also stem from the lower environmental standards and regulatory intensity in developing countries, leading to a "pollution refuge" effect and "carbon leakage" problems. Then, it will hinder improvements in carbon performance [48].

3.3. Model Specification

This paper used regression analysis to examine the research hypotheses. In order to avoid that the individual differences among different cities may influence results, a fixed-effect model was used to test the above hypotheses. The basic model is as follows:

$$\ln\mathrm{CP}_{it} = \alpha_0 + \alpha_1 \ln\mathrm{UL}_{it} + \alpha_2 city_{it} + \varepsilon_{it} \tag{3}$$

where CP represents the CP, measured by the net carbon sink efficiency. UL refers to urbanization level, measured by the comprehensive level of population urbanization, economic urbanization and spatial urbanization. i,t indicates that the individual effect and the temporal effect are controlled in the model. α_1 is the impact coefficient of UL on CP, which responds to Hypothesis 1. If $\alpha_1 > 0$, it indicates that the contribution of the positive externalities of the agglomeration effect to CP is greater than the "inhibition" effect of the crowding effect on CP. In other words, UL has a significant positive impact on CP.

In order to further analyze the impact path of urbanization on CP, this paper constructed the mechanism test model as follows. The basic idea is to first test the impact of urbanization on the relevant mechanism variables, and then test the impact of the mechanism variables on CP:

$$\ln\mathrm{LD}_{it} = \beta_0 + \beta_1 \ln\mathrm{UL}_{it} + \beta_2 city_{it} + \varepsilon_{it} \tag{4}$$

$$\ln\mathrm{CP}_{it} = \gamma_0 + \gamma_1 \ln\mathrm{UL}_{it} + \gamma_2 \ln\mathrm{LD}_{it} + \gamma_3 city_{it} + \varepsilon_{it} \tag{5}$$

where LD represents the land-development intensity, measured by the proportion of urban land in the total land area. β_1 and γ_2 are used to examine the second hypothesis. If $\beta_1 > 0$ and $\beta_1 < 0$, with $p \leq 0.5$, it indicates that UL will hinder CP through LD, which supports Hypothesis 2:

$$\ln\mathrm{LE}_{it} = \mu_0 + \mu_1 \ln\mathrm{UL}_{it} + \mu_2 city_{it} + \varepsilon_{it} \tag{6}$$

$$\ln\mathrm{CP}_{it} = \omega_0 + \omega_1 \ln\mathrm{UL}_{it} + \omega_2 \ln\mathrm{LD}_{it} + \omega_3 city_{it} + \varepsilon_{it} \tag{7}$$

Similarly, LE denotes the land-use efficiency, measured by the the ratio of GDP to total land area. If $\mu_1 > 0$ $\omega_2 > 0$, with $p \leq 0.5$, it indicates that UL will help CP through LE, which supports Hypothesis 3.

3.4. Data Resource

The vector data of administrative boundaries and the land use data with 30 m × 30 m resolution during 2000 to 2020 are from the Resource and Environmental Science Data Center of the Chinese Academy of Sciences. The socio-economic data are derived from the China Urban Statistical Yearbook (2001–2021), and the corresponding provincial statistical yearbooks. Carbon emissions and carbon absorption data at the city scale from 2000–2020 of 1 km × 1 km are derived from the data published by Scientific Data [49], which are estimated by using a particle swarm optimization–back propagation algorithm to unify the scale of DMSP/OLS, NPP/VIIRS satellite imagery and MOD17A3 products.

4. Results

4.1. Spatial–Temporal Characteristic of UL and CP

Figure 3 displays the spatial distribution of UL from 2000 to 2020. Cities with higher value of UL are mainly located in the eastern and southern areas. Specifically, Shanghai is the region with the highest level of urbanization, followed by Nanjing and Wuxi in Jiangsu Province, Anqing and Wuhu in Anhui province, and Hangzhou, Shaoxing, Ningbo, Taizhou, and Wenzhou in Zhejiang province in 2000. In 2020, the areas with the highest UL are concentrated in Nanjing, Wuxi, Suzhou, and Hangzhou. Compared with 2000, cities with lower values of UL are scattered, such as Suzhou, Bozhou, and Fuyang in northern Anhui, and Xuancheng and Huangshan in southern Anhu.

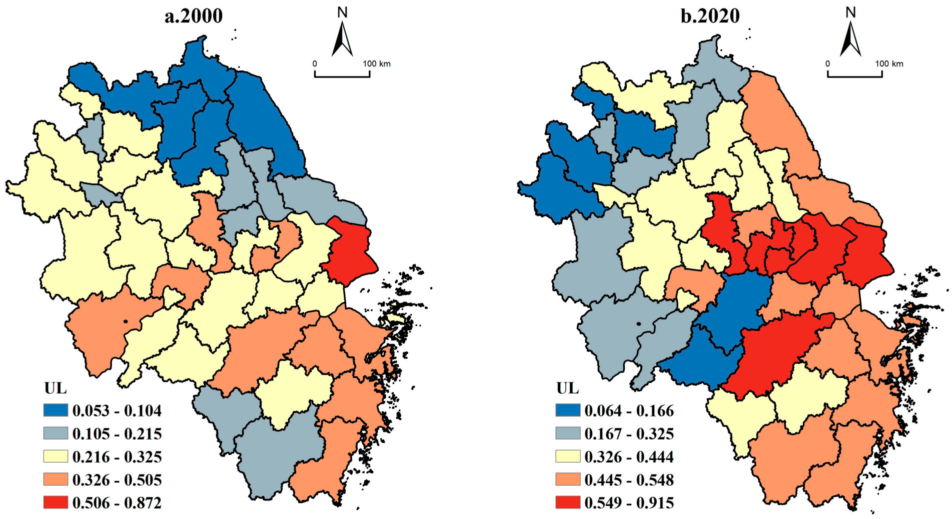

Figure 3. Spatial distribution of UL in 2000 and 2020.

Figure 4 displays the spatial pattern of CP. Cities with a high value of CP are mainly concentrated in southwest Zhejiang, southern Anhui, and southern Jiangsu in 2000. There are increasing trends in CP consistent with the change of UL. And cities with a high value of CP are located in northern Jiangsu in 2020. In general, cities with a higher level of urbanization generally have higher CP. This may mean that the increase in urbanization has accelerated the improvement of CP and contributed to the achievement of carbon neutrality goals.

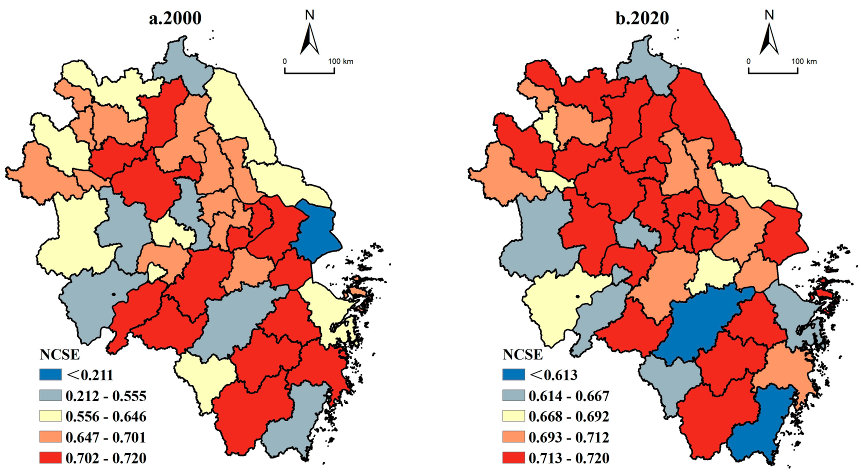

Figure 4. Spatial distribution of CP in 2000 and 2020.

4.2. The Impact of UL on CP

4.2.1. Results for Baseline Model

Table 2 reports the effects of UL on CP. Models (1–5) examine the impact of UL on CP in the YRD, Shanghai, Jiangsu, Zhejiang, and Anhui provinces, respectively. Coefficients of lnUL in these models are statistically significant and positive, supporting Hypothesis 1. Namely, UL can help CP. From the perspective of the magnitude of the impact coefficient, for every 1% increase in UL, the CP will increase by 0.149%, 0.035%, 0.058%, 0.241%, and 0.126% in YRD, Shanghai, Jiangsu, Zhejiang, and Anhui provinces, respectively. Zhejiang province is more susceptible to the influence of urbanization.

Table 2. Effects of UL on CP.

Model	YRD	Jiangsu Province	Zhejiang Province	Anhui Province
	(1)	**(3)**	**(4)**	**(5)**
LnUL	0.149 ** (1.960)	0.058 * (0.900)	0.241 *** (3.551)	0.126 *** (4.761)
LnPD	0.038 *** (4.002)	0.047 * (1.817)	0.050 ** (2.119)	−0.027 ** (−3.270)
LnEI	0.064 *** (4.991)	0.108 *** (5.224)	0.179 *** (7.416)	−0.048 *** (−9.721)
LnIS	0.027 * (1.918)	−0.133 *** (−4.068)	−0.011 (−0.321)	0.069 *** (7.664)
LnRD	−0.041 *** (−5.174)	−0.018 (−1.591)	−0.044 *** (−6.666)	−0.021 * (−1.757)
LnFI	−0.021 *** (−2.939)	−0.028 ** (−2.397)	−0.084 *** (−10.070)	0.021 ** (2.443)
LnOL	0.003 *** (7.654)	−0.014 *** (−12.658)	0.001 (0.081)	0.008 ** (1.125)
Constant	0.653 *** (8.465)	0.970 *** (12.920)	0.174 (0.479)	0.303 (−0.958)
R^2	0.854	0.923	0.763	0.918
Time-fixed	Yes	Yes	Yes	Yes
Obs	820	260	220	320

Note: *, **, *** are 1%, 5%, and 10% significance, respectively.

As the core city of the YRD, Shanghai has a high population density and intensive economic activities. Thus, it will consume more material resources and emit more carbon dioxide. Due to its geographical proximity to Shanghai, the urbanization development of Jiangsu Province has been strongly driven by Shanghai's radiation. These facts have led to significant pressure on Jiangsu province to reduce energy consumption and improve CP. In contrast, the mountainous terrain of southern Anhui and the mountainous and hilly geographical characteristics of Zhejiang Province have limited urban development and construction activities, which in turn is conducive to improvement of CP.

4.2.2. Has the Land-Development Intensity Decreased the Carbon Performance?

Table 3 reports the impact of LD on CP. Coefficient of lnUL in model (6) exhibits the relationship between UL and LD. The coefficient is positive, with $p < 0.01$, indicating that the rapid development of urbanization can significantly increase LD, which is consistent with Hypothesis 2. Specifically, for every 1% increase in UL, the LD will increase by 0.413%.

The coefficient of lnCP in model (7) reports the relationship between LD and CP in YRD. For every 1% increase in LD, the CP will decrease by 0.024%. Hence, for every 1% increase in UL, the CP will decrease by approximately 0.010% through LD in the YRD.

Table 3. Results of land-development intensity on carbon emission performance.

Model	YRD		Jiangsu Province		Zhejiang Province		Anhui Province	
	LnLD (6)	**lnCP (7)**	**LnLD (10)**	**lnCP (11)**	**LnLD (12)**	**lnCP (13)**	**LnLD (14)**	**lnCP (15)**
lnLD		−0.024 *** (−3.624)		−0.016 * (−1.657)		−0.024 * (−1.954)		0.013 ** (1.325)
LnUL	0.413 *** (7.240)		0.920 *** (7.126)		0.049 *** (8.759)		0.383 ** (2.445)	
LnPD	0.202 *** (9.199)	−0.032 *** (−2.580)	0.558 *** (4.518)	−0.055 ** (−2.081)	0.071 ** (1.540)	0.026 ** (1.131)	0.772 *** (6.077)	0.020 ** (2.074)
LnEI	0.090 ** (1.374)	0.047 *** (4.191)	0.310 ** (2.445)	0.098 *** (5.524)	0.468 *** (7.518)	0.154 *** (6.254)	0.376 *** (3.620)	−0.052 ** (−2.258)
LnTP	−0.273 *** (−18.637)	0.002* (0.283)	0.277 *** (13.791)	0.004* (0.326)	0.080 * (0.975)	0.025 * (1.745)	0.225 *** (5.412)	0.025 ** (1.460)
LnIS	−0.955 *** (−13.006)	0.006 * (0.396)	0.447 ** (2.233)	−0.146 *** (−4.450)	0.978 *** (9.176)	−0.084 *** (−2.627)	0.570 *** (5.121)	−0.004 ** (−0.503)
LnRD	0.290 *** (7.061)	−0.052 *** (−6.448)	0.446 *** (16.339)	−0.033 *** (−2.766)	0.643 *** (8.016)	0.055 *** (2.913)	−0.156 ** (−2.172)	0.035 * (1.794)
LnFI	−0.083 ** (−2.300)	−0.018 *** (−2.684)	0.317 *** (14.402)	−0.029 ** (−2.503)	−0.475 *** (−9.199)	0.067 *** (3.803)	−0.046 (−0.896)	−0.011 (−0.909)
LnOL	0.045 * (1.881)	0.002 * (0.408)	−0.070 * (−1.524)	−0.015 *** (−2.890)	0.093 ** (2.304)	−0.004 * (−0.603)	0.078 * (1.768)	0.014 (1.552)
Constant	−1.636 * (−1.689)	0.773 *** (4.413)	−2.220 ** (−3.090)	−1.206 *** (−4.433)	10.880 *** (10.413)	−0.875 ** (−2.471)	1.271 *** (4.971)	0.331 ** (1.042)
R^2	0.951	0.769	0.876	0.782	0.776	0.903	0.982	0.723
Time-fixed	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Obs	820	820	260	260	220	220	320	320

Note: *, **, *** are 1%, 5%, and 10% significance, respectively.

From the perspective of regional differences, the coefficients of lnUL in model (8,10,12,14) show the relationship between UL and LD in Shanghai, Jiangsu, Zhejiang, and Anhui, respectively, with $p < 1\%$, $p < 5\%$, $p < 5\%$, and $p < 1\%$, respectively. Specifically, as with 1% increase in UL, LD will increase about 1.006%, 0.920%, 0.049%, and 0.383% in the different, areas respectively. The impact of UL on LD is consistent with the level of economic development, the hierarchical administrative authorities, as well as with natural endowment. As centrally administrated municipalities, the rapid economic growth and the population agglomeration in Shanghai have led to drastic changes in land-use change. In contrast, Zhejiang Province is limited by the natural conditions of mountains and hills, resulting in a lower level of LD.

The coefficients of lnLD in model (9,11,13,15) are the results of the impact of LD on CP, respectively. Specifically, for every 1% increase in LD, CP will decrease about 0.267%, 0.016%, 0.024%, and 0.013% in Shanghai, Jiangsu, Zhejiang, and Anhui, respectively. Overall, as the UL increases by 1%, CP will decline by approximately 0.269%, 0.015%, 0.001%, and 0.0049 in Shanghai, Jiangsu province, and Zhejiang province, respectively, while it will increase by 0.005% in Anhui province. These findings support Hypothesis 2 that rapid urbanization can increase LD, which ultimately will reduce regional CP.

4.2.3. Has the Land-Use Efficiency Increased the Carbon Performance?

Table 4 reports the results of LE on CP. The coefficient of lnLE in model (12) shows that as the UL increases by 1%, LE will increase 1.342% in the YRD. And the coefficient of lnCP in model (13) shows with a 1% increase in LE that CP will increase by 0.047%. Overall, for every 1% increase in UL, CP will increase 0.063% through LE, which supports Hypothesis 3; namely, the rapid urbanization has improved the LE, which could reduce carbon emissions. From the perspective of regional differences, the coefficients of lnUL in model (14,16,18,20) exhibit the results of the impact of UL on LE. As UL increases by 1%, LE will increase by 1.494%, 0.640%, 0.168%, and 0.227%, in Shanghai, Jiangsu, Zhejiang, and Anhui, respectively. Therefore, the gap in the UL will produce different impacts on LE. Cities with higher UL have a higher effect on LE than cities with lower UL.

Table 4. Results of land-use efficiency on carbon emission performance.

Model	**YRD**		**Jiangsu Province**		**Zhejiang Province**		**Anhui Province**	
	LnLE (12)	**CP (13)**	**LnLE (16)**	**CP (17)**	**LnLE (18)**	**CP (19)**	**LnLE (20)**	**CP (21)**
lnLE		0.047 *** (3.219)		0.033 *** (5.264)		0.038 ** (−3.269)		0.014 ** (−4.127)
LnUL	1.342 ** (2.486)		0.640 ** (2.986)		0.168 ** (3.393)		0.227* (1.257)	
LnPD	0.012 ** (2.998)	0.037 *** (5.117)	0.026 ** (1.292)	0.046 *** (1.785)	0.024 (0.448)	0.020 ** (2.870)	0.022 (0.473)	−0.037 * (−1.685)
LnEI	0.011 *** (4.617)	0.051 *** (3.659)	0.021 ** (1.161)	0.099 *** (5.520)	0.024 (0.066)	0.163 *** (6.697)	0.018 (0.411)	−0.016 * (−1.935)
LnTP	0.006 * (1.769)	−0.005 ** (−4.124)	0.012 ** (0.937)	−0.007 ** (−3.569)	0.015 (1.414)	−0.026 * (−1.767)	0.007 (0.558)	−0.009 ** (−2.198)
LnIS	0.014 ** (2.041)	0.029 ** (3.219)	0.033 *** (5.960)	−0.137 *** (−4.214)	0.034 *** (9.243)	−0.068 ** (−2.195)	0.019 *** (5.371)	0.045 ** (3.380)
LnRD	0.011 *** (5.473)	−0.061 *** (−7.926)	0.011 *** (6.218)	−0.023 ** (−2.229)	0.017 *** (8.161)	0.000 *** (5.142)	0.012 *** (7.142)	0.017 *** (8.251)
LnFI	0.024 * (0.191)	0.037* (1.251)	0.012 ** (3.919)	−0.025 ** (−2.233)	0.017 (1.263)	−0.116 *** (−4.777)	0.009 (0.169)	−0.002 (−0.107)
LnOL	0.005 * (0.643)	0.003* (2.621)	0.005 *** (11.182)	−0.016 *** (−7.971)	0.007 *** (8.215)	−0.003 ** (−3.365)	0.007 (1.094)	0.012 ** (4.504)
Constant	0.191 (1.102)	−0.631 (−0.093)	0.332 *** (15.142)	−1.144 *** (−4.231)	0.364 (0.517)	−1.040 ** (−2.130)	0.316 (0.103)	0.043 * (1.103)
R^2	0.954	0.823	0.921	0.952	0.933	0.922	0.786	0.912
Time-fixed	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Obs	820	820	260	260	220	220	320	320

Note: *, **, *** are 1%, 5%, and 10% significance, respectively.

The coefficients of lnLE in model (15,17,19,21) indicate that as the LE increases by 1%, CP will increase 0.037%, 0.033%, 0.038%, and 0.014%, in Shanghai, Jiangsu province, Zhejiang province, and Anhui province, respectively. Namely, for every 1% increase in UL, CP will increase 0.063%, 0.021%, 0.006%, and 0.003% through LE, respectively. Among them, urbanization in Shanghai has a stronger positive impact on CP by improving LE.

The reason behind this is that as the most urbanized and economically developed city, Shanghai has attracted a large number of industries with strong profitability and small land footprint, which often have irreputable advantages in energy efficiency and green production technologies, thus effectively conserving natural resources and optimizing CP. Therefore, urban land expansion is inevitable, but the improvement of LE can effectively compensate or offset the carbon emissions caused by the increase in LD.

4.3. Robustness Test

This paper tested the robustness of the empirical analysis results from two aspects, including substitution variables and verification of endogeneity. First, considering the existence of alternative indicators for the explanatory variables and core explanatory variables, this study further replaced the explanatory variables with the comprehensive levels of population urbanization, land urbanization, and social urbanization, and the results show that urbanization still has a significant impact on CP. In addition, a similar conclusion can still be drawn by replacing the core explanatory variable with the commonly used carbon emission intensity (Tables S1–S3). Finally, the explanatory variable and the core explanatory variable were replaced at the same time, and the results were still robust. It is worth noting that the analysis of regional differences in this paper can also be used as one of the robustness tests.

In addition, considering the endogeneity problems that may arise in the empirical analysis, the lag effect is further added to the fixed-effect model. That is, urbanization in the current period may affect CP or land-use change in this period and beyond, but not CP or land-use change before the period. The results continue to show agreement with the conclusions already established in this paper. Therefore, it is reasonable to assume that the theoretical analysis and empirical tests of this paper have strong robustness.

5. Discussion

5.1. Urbanization and Carbon Emission Performance

Urbanization has a significant positive impact on CP, suggesting that rapid urbanization is not in conflict with the goal of carbon neutrality. As an intrinsic mechanism of urban growth, agglomeration dynamics determines the differential impact of urbanization on CP [50]. Our results indicates that urbanization is expected to contribute to helping achieve carbon neutrality on time or even ahead of schedule through balancing the positive and negative externalities of agglomeration, which confirms the effectiveness of existing views. Hence, increasing the positive externalities of agglomeration and reducing negative externalities are key to achieving sustainable urban growth and mitigating climate change.

5.2. Urbanization, Land-Use Change and Carbon Emission Performance

The paper identified land-use change as a mediator in the impact of urbanization on CP. The rapid urbanization growth and economic development in China are manifested by the significant change in LD and LE. The former is mainly manifested in the decrease of soil and vegetation carbon storage in natural ecosystems and the increase in consumption of energy and resources [51]. The latter affects CP by changing the industrial structure and resource allocation [52].

This paper suggests that LD can worsen CP. Previous research results show that cities with developed urbanization are those with high population density, intensive economic activities, and high industrial agglomeration, which increase the consumption of energy resources, as well as the demand for land of housing, commerce, and public service facilities. Further, LD will increase carbon emissions through encroaching on green ecological land and consuming energy and resources. In addition, changes in LD are intrinsically related to the fiscal purpose of the region. In many cities, the chain of "land finance–real estate–local economy" has been identified as a key determinant in urban economic growth [53]. In this regard, the preference for investing in real estate can lead to resource misallocation, blind expansion of urban land, and crowding out investment in innovation [54], thereby increasing the pressure on carbon emissions. In response, a moderate LD is the key to coordinating the relationship between UL and CP.

Conversely, as another manifestation of land-use change, increasing LE can help to improve CP. Specifically, LE can decouple urban growth from energy resource consumption by reducing the need for new urban land. In addition, a city with high LE means that the city has a high level of knowledge of spillover effect and a highly specialized industrial layout. Therefore, the land-use efficiency improves the CP by optimizing the allocation of land resources and adjusting the structure of land supply and demand. Third, high-efficiency activities can gradually replace the low-efficiency ones, leading to a decline in carbon emissions [55]. In addition, the empirical finding in the YRD reveals that for every 1% increase in UL, the CP will decrease by approximately 0.010% through LD and increase 0.063% through LE, respectively. In such a case, the negative effect of LD on CP may be partially offset by LE. Hence, improving LE may be an effective way to address the conflict between urban growth and environmental pollution.

5.3. Regional Heterogeneity

There is regional heterogeneity in the impact of urbanization on CP. Specifically, the positive impact of urbanization on CP in Zhejiang province is 6.89 times, 4.16 times, and 1.91 times larger than that in Shanghai city, Jiangsu province, and Anhui province, respectively. Such a mechanism may be related to the characteristics of resources and environment, the type of economic activities, the intensity of human activities, and the quality of habitats [56]. For example, the mountainous and hilly geographical environment determines that cities in Zhejiang do not have access to the same growth rate and development opportunities as cities in Shanghai in terms of population density, industrial scale, and urbanization expansion. Hence, resource consumption and carbon emissions in Zhejiang are much lower than those of Shanghai [57], while the area of land with high carbon sinks is much higher than that of Shanghai, thereby showing different CP. Therefore, considering the regional heterogeneity of the impact of urbanization on CP will help to formulate more targeted urban development strategies [58].

5.4. Policy Implications

This paper has three following policy implications. First, it is fundamental to continue to develop vigorously the economy of urban agglomerations and promote regional economic integration. Although carbon emissions are inevitable during the process of urbanization, increasing the spatial concentration of economic activities can achieve significant energy conservation and emission reduction effects.

Second, it is necessary to implement a stricter policy on the supply of construction land. This paper suggests that the positive effects of UL on CP may be overshadowed by the drawbacks of rapid land expansion [51]. Therefore, it is necessary to formulate a stricter land use approval system and have more scientific urban planning to reduce the supply of new construction land, such as the renovation of old urban areas, urban renewal, and land reclamation.

Third, it is critical to capture the positive impact of land-use change on CP. Cities should focus on connotative development, which is considerable for sustainable development [59]. Therefore, policymakers should shift policies from the cult of GDP to environmental tolerance in order to realize land use as an effective tool to balance urbanization and carbon emissions.

6. Conclusions

To better understand how urbanization contributes to CP, this paper went beyond the conventional thinking of mathematical models or economic models, further concentrating on the role of agglomeration dynamics and land-use change. First, highly urbanized cities are those where a lot of interaction is possible and are therefore places where agglomeration is prominent. In turn, the high density of population and the prevalence of economic activity have led to higher CO_2 emissions. These findings complement the theoretical thinking on the relationship between the economic externalities and eco-environmental externalities of urbanization. That is, the impact of urbanization on CP largely depends on the trade-off between the positive externalities of the economy and the negative externalities of the ecological environment.

Second, through the mediator of land-use change, this paper distinguishes the internal influence mechanism of LD and LE on CP. Since the agglomeration effect is less unlikely to be captured intuitively, LD and LE determine the consumption of energy and resource allocation efficiency, which produces the heterogeneity of CP. Hence, this paper defines the different influences of land-use change and identifies their distinct CP.

The empirical results of the YRD indicate the following: (1) Urbanization can help to improve regional CP. Specifically, for every 1% increase in urbanization, CP will increase 0.149%. (2) As an important mediating variable, land-use change makes urbanization have different impacts on CP. Urbanization may hinder CP by increasing LD, while improving CP by promoting LE. Empirical findings reveal that for every 1% increase in urbanization level, the CP will decrease by approximately 0.010% through LD and increase 0.063% through LE, respectively. In such a case, the negative impact of an increase in LD is likely to be offset by benefits from improved LE.

There are some important limitations. First, this paper focuses on the single impact of LD or LE, while leaving out the critical role of their interactions in CP. Hence, identifying the impact of the interaction between LD and LE on CP at different stages of development will surely enrich the understanding of sustainable urban growth. Second, future research can further explore different impact paths, such as industrial restructuring and technological progress. Third, future research can add more study areas for comparative studies from the perspectives of differences in urbanization level, development stage, and geographical location. In addition, future research will further use the spatial autocorrelation model and the spatial panel economic model to consider the spatial correlation and spatial spillover effect of UL on CP. This may help to fully understand the mechanism of urbanization on CP.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/land14010012/s1, Table S1: Effects of UL on CP; Table S2: Results of land-development intensity on CP; Table S3: Results of land-use efficiency on CP.

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Abbreviations

CP carbon emission performance
UL urbanization level
LD land-development intensity
LE land-use efficiency

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