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Measuring Multi-Faceted Land Use Efficiency of Large-Scale Urban Agglomerations under Multi-Scale Drivers: Evidence from China

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Abstract: Although urban agglomerations are vital sites for national economic development, comprehensive multidimensional investigations of their performance are lacking. Accordingly, we examined land use efficiency from multiple perspectives in two of the earliest developed and most advanced urban agglomerations in China, the Beijing–Tianjin–Hebei (BTH) region and the Yangtze River Delta (YRD), using different metrics, including trans-regional drivers of the spatial allocation of construction land. We found that: (1) The land use efficiency of urban agglomerations was context dependent. Whereas it was higher in the Beijing–Tianjin–Hebei region for population density per unit area of construction land than in the Yangtze River Delta region, the opposite was true for gross domestic production. Thus, a single aspect did not fully reflect the land use efficiency of urban agglomerations. (2) The land use efficiency of the two urban agglomerations was also scale dependent, and in the Yangtze River Delta region, the use of multiple metrics induced variations between aggregate and local measures. Median values for the land use efficiency of cities within an urban agglomeration were the most representative for comparative purposes. (3) The drivers of the spatial allocation of construction land were trans-regional. At the regional scale, most topographical factors were restrictive. Major regional transport networks significantly influenced the occurrence of construction land near them. Dominant cities and urban areas within each city exerted remote effects on non-dominant cities and rural areas. In principle, the median value can be considered a promising metric for assessing an urban agglomeration's performance. We suggest that stringent management of land use in areas located along regional rail tracks/roadways may promote sustainable land use.

Keywords: urban agglomeration; urban land use efficiency; spatial inequality; trans-scale effects

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1. Introduction

Land use, which can be defined as the interaction of human activities and the natural environment, plays a vital role in promoting sustainable urbanization as well as environmental well-being, particularly in densely populated urban areas [1,2]. Urban land use efficiency (ULUE) is an important indicator for measuring land use performance, particularly in cities where land is becoming an increasingly scarce resource. Improving land use efficiency by maximizing the benefits of land use with minimal inputs of land resources and maximal gains of socioeconomic outputs is the main challenge currently facing land use planners and managers.

Urban land use efficiency can be defined in different ways from different perspectives [3]. Most studies have evaluated ULUE in terms of output gains relative to land resource inputs [4–6]. Because of the complexity of human activities, outputs are defined as demographic, social, economic, and ecological gains [7–9], which could lead to inconsistent results for ULUE [6]. Some studies have focused on one specific output gain from land inputs, such as population density or GDP output per unit of construction land [10–13]. For instance, Jiao et al. (2020) used urban population to quantify ULUE and explored the relation between ULUE and city size in China [8]. Liu et al. (2018) assessed the land use efficiency of China's construction land in terms of economic outputs relative to construction land inputs [14]. By contrast, other studies have used a composite indicator to measure land use efficiency entailing multiple inputs (e.g., inputs of land, labor, and investments) relative to multiple outputs (social, economic, and environmental and ecological outputs) [7,9]. Although on the one hand measuring ULUE according to a single dimension could lead to bias, on the other hand, given the complexity of human activities, a composite indicator of ULUE may obscure differences in ULUE associated with various facets. Up to now, no studies have simultaneously compared possible differences or even inconsistencies in ULUE measured using different indicators. Therefore, a study that comprehensively considers land use efficiency from different perspectives is pertinent for dense urban areas where various human activities co-exist.

Studies have shown that ULUE varies across different spatial domains and scales: global, national, regional, and city [2,9,14–17]. The UN 2030 Agenda for Sustainable Development Goals (SDG 11.3.1) includes the target of ensuring efficient urban land use [18,19]. Considering this target, some researchers have compared the land use efficiency of different world cities. For instance, Guneralp et al. (2020) found that land use efficiency had consistently declined in India, China, North America, and Europe and that the trends for small–medium and large urban areas differed [2]. Masini et al. (2019), who analyzed the land use efficiency of 417 metropolitan regions across 27 countries in Europe, found that land use efficiency was generally higher in affluent cities than in cities with large municipalities, landscape fragmentation, and low incomes [20]. Previous studies have mostly focused on individual cities rather than on urban agglomerations. The term urban agglomeration was originally proposed by the United Nation's Center for Human Clusters to cover related concepts, such as megalopolis, city-region, and city-cluster [21]. An urban agglomeration is not simply a loose cluster of cities; rather, the term refers to interconnected cities with one or more large/super cities. The strong effect of urban agglomeration is well known. For instance, in the United States, ten urban agglomerations cover less than 30% of the country's area but account for nearly 86% of the country's population. In Europe, the major 12 urban agglomerations cover 11.3% of the total area but account for approximately 69.6% of the total population [22–24]. In China, the Beijing–Tianjin–Hebei (BTH) urban agglomeration encompasses less than 3% of the national territorial area but accounts for 9.06% of China's population and contributes 10.12% of the national gross domestic production (GDP). However, despite the great socioeconomic benefits provided by urban agglomerations at the aggregate level, the disparities and inequalities within subregions are still a source of conflict [25–29], particularly in developing countries in Asia and Africa, where urban agglomerations are developing at a rapid pace. However, assessments of the land use efficiency of urban agglomerations that simultaneously consider different dimensions and spatial scales remain a gap in the literature.

Given the objective of achieving optimal land use efficiency, identification of the drivers of land use allocation is imperative, especially at the city level. Many studies have investigated the factors that influence the allocation of urban land from the perspectives of economic performance, social change, traffic volumes, and policy [9,16,30–32]. However, most studies have considered driving factors at the scale of individual cities [33–35], and have paid less attention to urban agglomerations [36,37]. According to the definition of urban agglomeration, internal city clusters are not formed spontaneously; rather, they are ordered and hierarchically interconnected via comprehensive modern transportation and information networks. Therefore, to achieve long-term integration and sustainable regional development, coordinated policies, planning, and infrastructure development in cities is necessary [21]. However, little is known about how the spatial interactions of different cities affect the allocation of urban land across an entire region. In other words, within a given urban agglomeration, how the land use of a certain city is affected by other cities is an underexplored question [17]. Consequently, an investigation of the factors driving land development from the subregional scale to the regional scale is of critical importance for providing decision makers and planners in urban agglomerations with inputs for synergistically optimizing patterns of land development across the entire region.

In this study, we addressed two research questions relating to large-scale agglomerations. The first is how can land use performance in urban agglomerations be comprehensively evaluated at multiple spatial scales and from multiple dimensions? Second, what are the factors driving land development in urban agglomerations? We aimed to answer these questions by developing a new analytical framework for examining the ULUE of two typical urban agglomerations in China from multiple perspectives. First, we developed a methodology to evaluate different dimensions of ULUE using multiple metrics. Second, we investigated the drivers of land development across different scales (the individual city scale and the regional scale encompassing all cities in an urban agglomeration). In light of our findings, we present a discussion on how a full consideration of ULUE can contribute to inputs for achieving optimal performances of urban agglomerations.

2. Data and Methods

2.1. Study Area

The Beijing–Tianjin–Hebei (BTH) urban agglomeration in northeastern China extends along the shores of the Bohai Sea and covers a total area of approximately 22.0×10^4 km^2. The Yangtze River Delta (YRD) urban agglomeration is located along China's eastern coast, bordering the East China Sea, and encompasses a total area of 21.2×10^4 km^2 (Figure 1). As of 2015, the BTH urban agglomeration comprised 13 cities, whereas the YRD urban agglomeration comprised 26 cities. Both urban agglomerations are important centers of urbanization and industrialization in China and continue to exhibit rapid urbanization trends. For instance, in 2015, the aggregate demographic urbanization levels (the ratio of the urban population to total population) of the BTH and YRD urban agglomerations were 62.72% and 69.49%, respectively. These figures were evidently higher than the national average of 56.1% in 2015 [38].

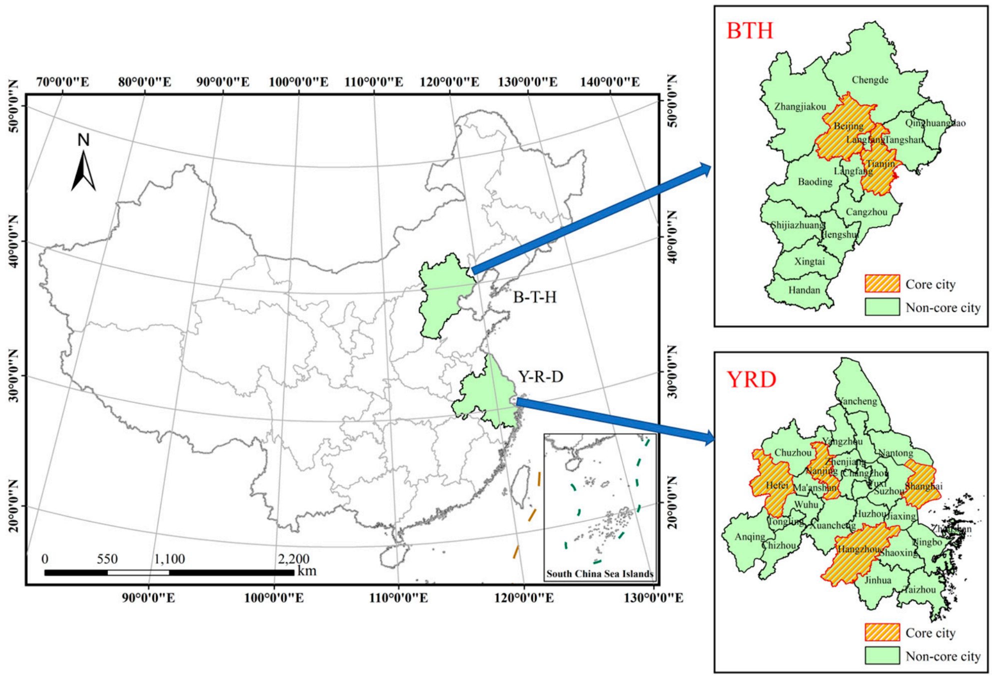

Figure 1. Spatial locations of Beijing–Tianjin–Hebei (BTH) and Yangtze River Delta (YRD) urban agglomerations in China.

2.2. Urban Land Use Efficiency

We used Landsat Thematic Mapper images (30 m) to map land use/land cover (LULC) types in 2015. The data were obtained from the open dataset of the Geospatial Data Cloud (http://www.gscloud.cn/, accessed on 1 March 2019). The LULC classification system was based on the characteristics of the BTH and YRD urban agglomerations and comprised six classes: forest, grass, water, farmland, construction land, and barren land. All types of construction land in urban and rural areas, such as land used for residential, commercial, industrial, and transportation purposes as well as public buildings, were included. Barren land mainly comprised areas with sand, bare soil, exposed rock, and strip mines and quarries. We used a stratified random sampling scheme to select locations within cities for comparing the image classifications to categorize land use data created through the visual interpretation of high spatial resolution SPOT-7 images (1.5 m), which was launced on 30 June 2014 by Airbus Defence and Space. The overall accuracy, Kappa statistic, and average producer's and user's accuracy exceeded 93%, 0.8%, 80% and 94%, respectively.

We evaluated the ULUE of the two urban agglomerations by calculating the relative input–output ratio based on the Cobb–Douglas production function [14,25], which is the simplest approach that is frequently used to identify production efficiency [9]. Given the differential impacts of various types of land use, we designed a framework to evaluate the ULUE of the BTH and YRD urban agglomerations considered from two dimensions and at two spatial scales (Figure 2).

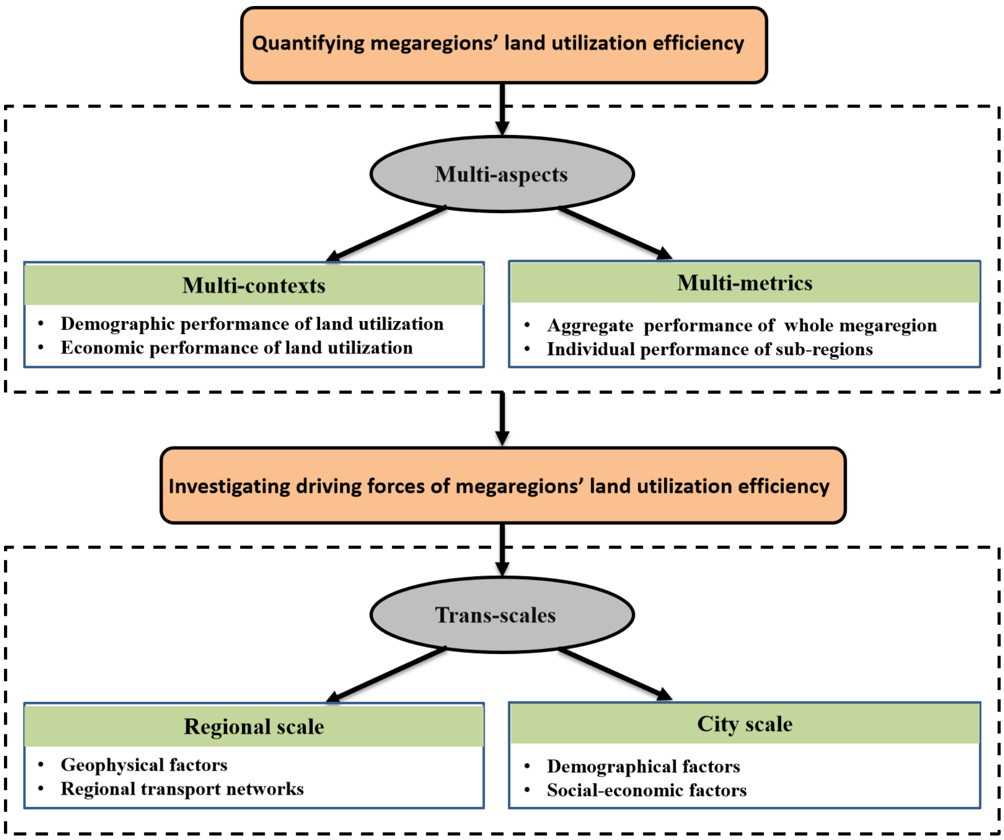

Figure 2. Framework for assessing the land use performance of large urban agglomerations.

For the first metric, we used the population density per unit of construction land to measure ULUE in terms of demographic performance. For the other metric, we used the GDP output per unit of construction land to measure the ULUE with respect to economic performance. Considering the multi-hierarchal structure of urban agglomerations, we examined the ULUE at the regional and city scales (i.e., regional and subregional scales).

At the regional scale (consisting of n cities), we calculated the overall aggregated ULUE using Equations (1) and (2)

$$ULUE\_PD_{region} = \frac{\sum_{i=1}^{n} Pop_i}{\sum_{i=1}^{n} ConL_i} \quad (1)$$

$$ULUE\_GDP_{region} = \frac{\sum_{i=1}^{n} GDP_i}{\sum_{i=1}^{n} ConL_i} \quad (2)$$

where $ULUE\_PD_{region}$ is the value of population density relating to the overall construction land across the entire urban agglomeration; $ULUE\_GDP_{region}$ is the value of the ratio of the GDP output to the overall construction land across the entire urban agglomeration; Pop_i is the value of the population of the ith city within the urban agglomeration; GDP_i is the GDP value for the ith city within the urban agglomeration; $ConL_i$ is the value of construction land in the ith city within the urban agglomeration.

At the subregional (city) scale, we calculated the average ULUE for each city using Equations (3) and (4) according to the efficiencies calculated for each city (Equations (5) and (6))

$$ULUE\_PD_{city\_ave} = \frac{\sum_{i=1}^{n} ULUE\_PD_{city\_i}}{n} \quad (3)$$

$$ULUE\_GDP_{city\_ave} = \frac{\sum_{i=1}^{n} ULUE\_GDP_{city\_i}}{n} \quad (4)$$

$$ULUE\_PD_{city\_i} = \frac{Pop_i}{ConL_i} \quad (5)$$

$$ULUE\_GDP_{city\_i} = \frac{GDP_i}{ConL_i} \quad (6)$$

where $ULUE\_PD_{city\_ave}$ is the average value of population density for all cities within the urban agglomeration; $ULUE\_GDP_{city\_ave}$ is the average GDP output per unit of construction land for all cities within the urban agglomeration; $ULUE\_PD_{city\_i}$ is the value of population density of the ith city in the urban agglomeration; $ULUE\_GDP_{city\_i}$ is the value of GDP per unit of construction land in the ith city within the urban agglomeration.

We obtained population and GDP data for each city from the City Urban Statistical Yearbook [38]. The amount of construction land was calculated on the basis of the LULC classification map. All data sets were for the year 2015 [38].

2.3. Drivers of Land Development

Construction land, considered as a basic input of ULUE, critically influences ULUE; greater inputs of construction land correspond to a lower ULUE relative to the same output. Thus, a better understanding of the factors driving the development of construction land is essential for regulating the amount of construction land. Particularly in urban agglomerations, the spatial evolution of construction land is determined not only by land allocation within individual cities but also by interactions among cities, such as the spilled effects of core cities on non-core cities. We investigated the potential driving factors that affect the spatial evolution of construction using multi-regression models incorporating multiple factors.

Although many studies have investigated the local driving factors of land development of an individual city [39,40] (Zhang et al., 2020; Huang et al., 2021), concerns about teleconnection or distant drivers of land development are increasing, particularly for large regions [1,41]. By referring to previous studies, we selected 12 variables according to the social and economic characteristics of the BTH and YRD urban agglomeration (Table 1, Figures 3 and 4) for use in the regressions [41]. Elevation, slope, distance to river network, and distance to coastline were chosen as variables representing the geophysical factors. The social variables were the proportion of the urban population, distance to core cities, distance to urban center, distance to highway, distance to national highway, and distance to railway. The economic variables were the proportion of secondary industry and the proportion of tertiary industry within the overall industrial structure.

Table 1. Factors Driving the Spatial Evolution of Construction Land in the Beijing–Tianjin–Hebei (BTH) and Yangtze River Delta (YRD) Urban Agglomerations.

Classification of Driving Forces Based on Spatial Relevance	Classification of Driving Forces Based on Social–Economic–Natural Attributes	Driving Forces
Regional-scale driving forces	Geophysical factors	Elevation/m Slope/° Distance to river/km Distance to coastline/km
	Social factors	Distance to railway/km Distance to national highway/km Distance to highway/km Distance to urban center/km Distance to core city/km
City-scale driving forces	Demographic factors Economic factors	Proportion of urban population/% Proportion of the secondary industry/% Proportion of the tertiary industry/%

Values for the elevation and slope variables were derived from a 90 × 90 m digital elevation map obtained from the Geospatial Data Cloud site (http://www.gscloud.cn, accessed on 1 June 2019) maintained by the Computer Network Information Center of the Chinese Academy of Sciences. Values for the distance to river and distance to coastline variables were calculated using the locations of rivers and coastlines that were visually derived from remote sensing images. Values for the proportion of the urban population, the proportion of secondary industry, and the proportion of tertiary industry variables were obtained from the municipal statistical data. All data used to derive these variables were for 2015 or as close to 2015 as possible.

Using these selected driving factors, we developed a multi-logistic regression model, which is a widely used method in LULC studies. The goal of the multi-logistic regression analysis was to assess the influence of driving factors on the locations of LULC [42]. The dependent variable in the logistic regression model was the probability of the development of construction land. The independent variables were the 12 influencing factors discussed above and shown in Table 1. To simplify the analysis, all the variables were transformed into the raster format using the same cell size. In addition, the goodness of fit of the logistic regression model was evaluated using the receiver operating characteristic (ROC) curve method, which is used to evaluate the predicted probabilities by comparing them with the observed values across the entire domain [41]. The area below the ROC curve represents the ROC value, whose prediction accuracy improves as it approaches unity [43].

In this study, the ROC value for each LULC type exceeded 0.7, indicating that the model was appropriate. The general model was expressed as shown in Equation (7) below

$$\log\left(\frac{P}{1-P}\right) = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_n x_n \tag{7}$$

where P is the probability of the development of construction land within a grid cell, X_i is the driving factor, and β_0 is a constant. The β_i parameters (i = 1, 2, 3, . . . , m) denote the coefficients of each independent variable to be estimated, which could reveal the possible impact of each independent variable on the dependent variable.

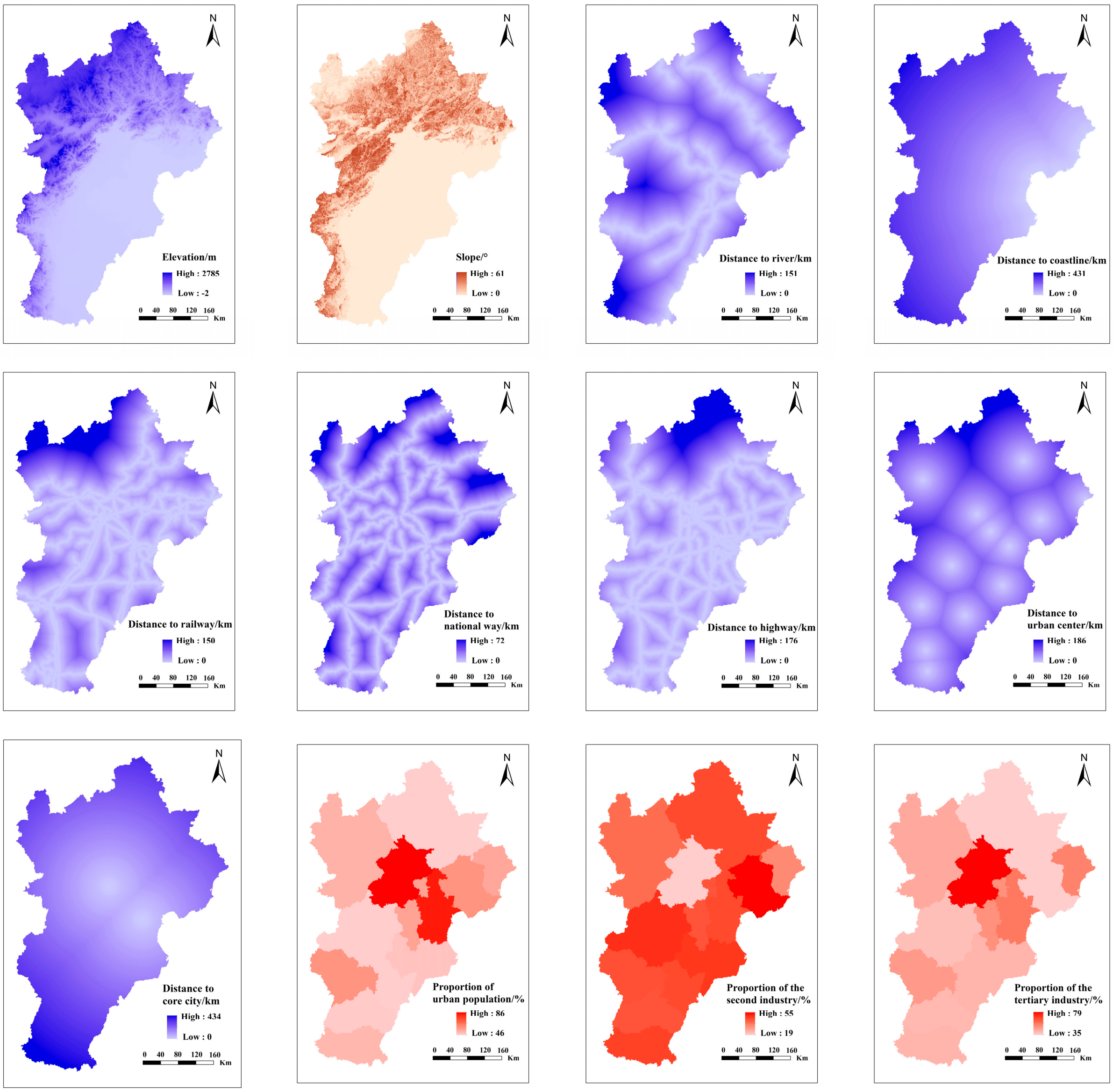

Figure 3. Spatial mapping of the drivers of construction land development in the BTH urban agglomeration [41].

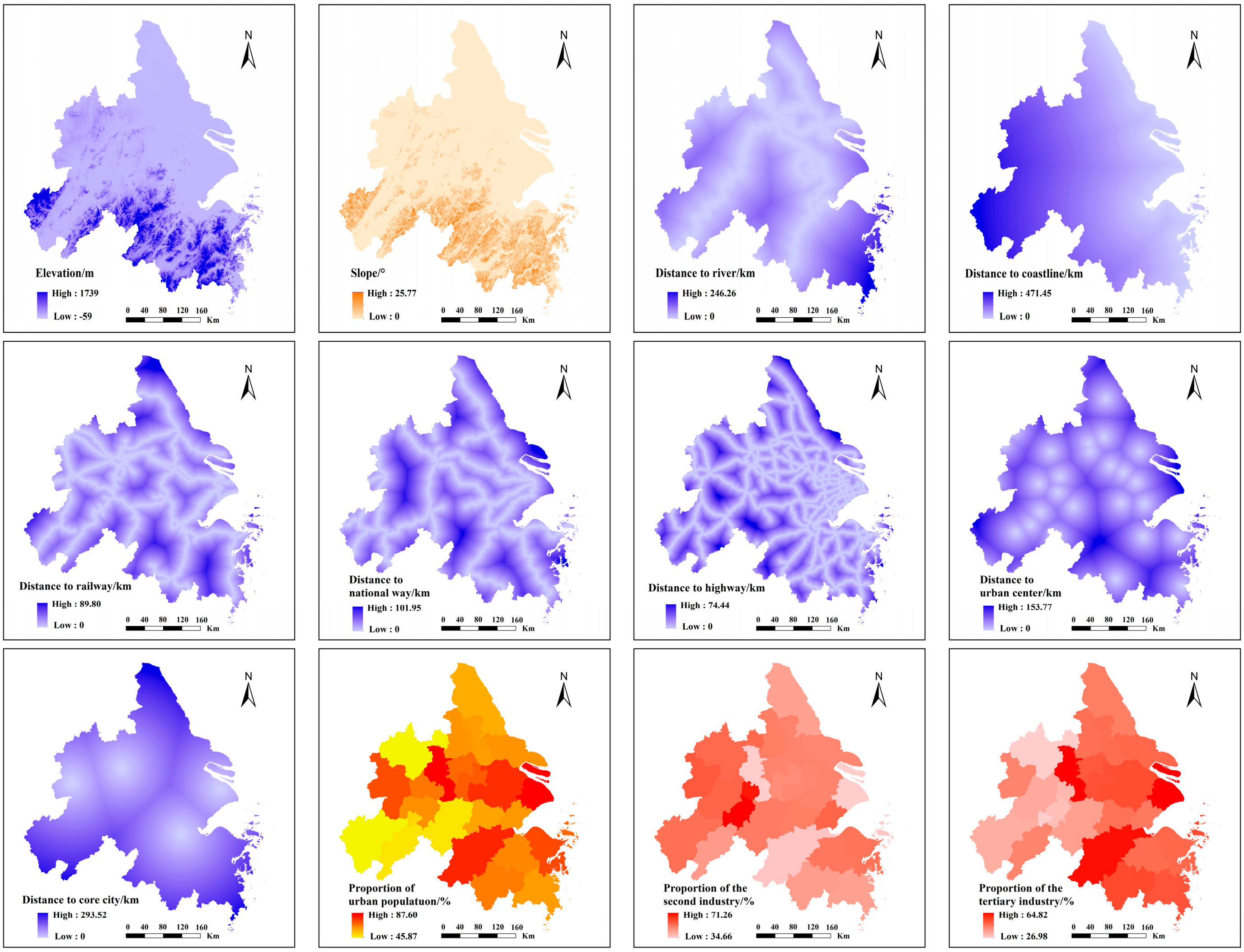

Figure 4. Spatial mapping of the drivers of construction land development in the YRD urban agglomeration.

3. Results

3.1. Urban Land Use Efficiency of Urban Agglomerations

ULUE values varied for different dimensions and revealed distinct differences at different spatial scales (Tables 2 and 3 and Figure 5). At the aggregate level, the ULUE value obtained from the GDP output per unit of construction land, was higher in the YRD urban agglomeration (35,958 $\times$ 10^4 RMB/km^2) than that of the BTH urban agglomeration (28,716 $\times$ 10^4 RMB/km^2) in 2015 (Table 2, Figure 5a,c), whereas the ULUE value for population density per unit of construction land of the YRD urban agglomeration (3993 persons/km^2) was lower than that of the BTH urban agglomeration (4581 persons/km^2) (Table 3, Figure 5b,d).

Table 2. Urban land use efficiency (ULUE) values obtained for the GDP output per unit of construction land in the BTH and YRD urban agglomerations.

ULUE Quantification in Terms of the GDP Output per Unit of Construction Land (RMB/km^2)		BTH	YRD
ULUE at aggregate level	Aggregate	28,716	35,958
ULUE at city level	Average	23,697	34,923
	Median	16,829	31,752
	Max	74,854	91,173
	Min	9027	9470

Table 3. ULUE values obtained for the population density per unit of construction land in the BTH and YRD urban agglomerations.

ULUE Quantification in Terms of Population Density per Unit of Construction land (Persons/km^2)		BTH	YRD
ULUE at aggregate level	Aggregate	4581	3993
ULUE at city level	Average	4398	4256
	Median	4471	4010
	Max	7061	8765
	Min	3055	2218

At the city level, the ULUE values evidently differed within urban agglomerations (Table 2, Figure 5a,c). For example, the ULUE values for the average GDP output per unit of construction land in the 13 cities within the BTH urban agglomeration ranged between 9027 $\times$ 10^4 RMB/km^2 and 74,854 $\times$ 10^4 RMB/km^2, with an average value of 23,697 $\times$ 10^4 RMB/km^2. By comparison, the ULUE values for the average GDP output per unit of construction land in the 26 cities within the YRD urban agglomeration varied between 9470 $\times$ 10^4 RMB/km^2 and 91,173 $\times$ 10^4 RMB/km^2, with an average value of 34,923 $\times$ 10^4 RMB/km^2. Only two out of the 13 cities (15.4%) within the BTH urban agglomeration had higher ULUE values than the estimated value at the aggregate level, whereas 11 out of 26 cities (42.3%) within the YRD urban agglomeration had higher ULUE values than the estimated aggregate value.

Moreover, ULUE values for the population density per unit of construction land at the city level also showed significant intercity variation within urban agglomerations (Table 3, Figure 5b,d). The average ULUE value for population density per unit of construction land in cities within the BTH urban agglomeration was 4398 persons/km^2, ranging from 3055 to 7061 persons/km^2 for different cities. Five of the 13 cities (38.5%) in the BTH had ULUE values for population density per unit of construction land higher than the estimated aggregated value. In the YRD urban agglomeration, the average value for population density per unit of construction land in cities was 4256 persons/km^2, ranging between 2218 and 8765 persons/km^2. Of the 26 cities in the YRD urban agglomeration, 13 (50.0%) had ULUE values for population density per unit of construction land higher than the estimated aggregate value.

The median ULUE values of different cities within the two urban agglomerations differed markedly from the aggregate and city-level values (Tables 2 and 3; Figures 4 and 5). For example, the median ULUE values for GDP output per unit of construction land in both urban agglomerations were clearly lower than the respective estimates at both the aggregate and city average levels (Table 2). However, the median values for the population densities in both urban agglomerations were in between the estimates in the respective urban agglomerations at the aggregate and city average levels.

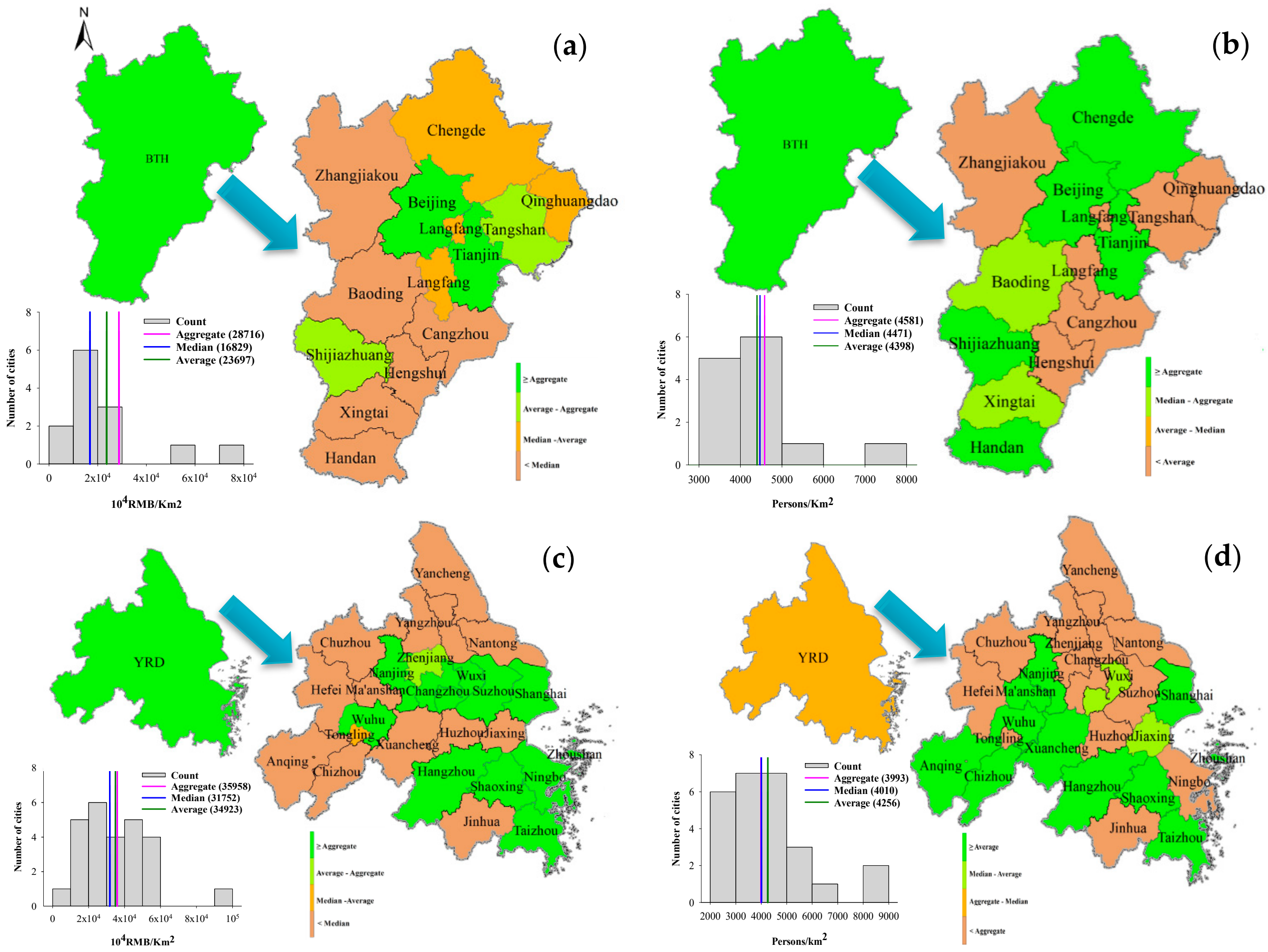

Figure 5. Comparisons of ULUE values according to different metrics. GDP output per unit of construction land in the BTH urban agglomeration (**a**), population density per unit of construction land in the BTH urban agglomeration (**b**), GDP output per unit of construction land in the YRD urban agglomeration (**c**), and population density per unit of construction land in the YRD urban agglomeration (**d**).

3.2. Factors Driving Land Development in Urban Agglomerations

Table 4 presents the results of the regression analyses. The spatial development of construction land was well explained by the various driving variables (Table 1) used in logistic regression, as indicated by the high ROC test values (ROC value = 0.85 (YRD); ROC = 0.86 (BTH)). However, not all of the driving factors listed in Table 1 were actually included in the regression models for both regions, and the factors that were included had differential impacts in the BTH and YRD urban agglomerations.

In general, most physical factors were significantly negatively related to the development of construction land in both urban agglomerations (Table 4). For example, the location of construction land in the YRD urban agglomeration was significantly negatively related to elevation, slope, distance to river, and distance to coastline. Of these variables, slope had the greatest impact on the spatial development of construction land. By contrast, in the BTH urban agglomeration, elevation and slope also posed evident constraints relating to the allocation of construction land; construction land tended to be prevalent in areas closer to the coastline.

Table 4. Contribution of driving factors to the spatial development of construction land in the BTH and YRD urban agglomerations. The significance of all included variables was less than 0.05.

Drivers of Spatial Development of Construction Land	BTH Urban Agglomeration		YRD Urban Agglomeration	
	Beta	Exp (B)	Beta	Exp (B)
Elevation/m	−0.001	0.999	−0.004	0.996
Slope/°	−0.134	0.874	−0.24	0.787
Distance to river/km			−0.003	0.997
Distance to coastline/km	0.002	1.002	−0.001	0.999
Distance to railway/km	−0.002	0.998	−0.003	0.997
Distance to national highway/km			0.001	1.001
Distance to highway/km	−0.006	0.994	−0.018	0.983
Distance to urban center/km	0.002	1.002	0.005	1.005
Distance to core city/km			0.003	1.003
Proportion of urban population/%			−0.004	0.996
Proportion of the secondary industry/%			0.013	1.014
Proportion of the tertiary industry/%	−0.013	0.987	0.005	1.005
Constant	−3.500	−3.500	−3.311	0.036
ROC value	0.86		0.85	

Moreover, transport routes had a significant effect on the development of construction land in the BTH and YRD urban agglomerations. For instance, the distance to railway and distance to highway within both urban agglomerations were negatively related to the development of construction land, indicating that relatively more construction land was allocated in close proximity to these transport routes. Additionally, both the dominant cities and core urban areas of each city had significant effects on the spatial development of construction land within an entire urban agglomeration. For example, for both the BTH and YRD urban agglomerations, the core urban area of each city had significantly positive impacts on the development of construction land in distant rural areas within the respective urban agglomerations. Moreover, for the YRD urban agglomeration, the distribution of dominant cities had significantly positive impacts on the development of construction land in other cities throughout the entire urban agglomeration. For instance, the relation between distance to core city and occurrence of construction land was significantly positive, indicating that relatively more land was allocated for construction in cities further away from the core cities of the YRD.

Apart from factors driving the spatial locations of construction land at the regional scale, socioeconomic factors at the city level also had significant impacts on the development of construction land, but these impacts varied across urban agglomerations. For instance, in the YRD urban agglomeration, the proportion of urban population was negatively related to the development of construction land, whereas the proportion of secondary industry and the proportion of tertiary industry were positively related to the development of construction land. In the BTH urban agglomeration, the proportion of tertiary industry was negatively related to the development of construction land, and the proportion of the urban population had no significant relationship with the development of construction land.

4. Discussion

4.1. Different Faceted Performance of Urban Agglomerations

We developed a two-dimensional and two-spatial scale framework for comprehensively quantifying the ULUE of two of China's urban agglomerations. Our findings indicated that when assessed in differing contexts using varying metrics within and between urban agglomerations, ULUE values of urban megaregions were inconsistent. Despite the overall higher GDP outputs and population densities relative to regional and national levels, the ULUE variations, considered from different angles, raise questions about the actual ULUE of urban agglomerations and underscore the importance of applying different perspectives to assess ULUE that is required to make informed decisions.

The inconsistency of ULUE values obtained in assessments of different dimensions of urban agglomerations suggests that ULUE is context dependent, with demographic and economic activities, entailing different dimensions, having different effects on land use efficiency. For example, when ULUE was considered from the perspective of population density relating to construction land, the overall aggregated ULUE in the BTH region was greater than that in the YRD. However, the aggregate value for the ULUE in the BTH urban agglomeration relating to GDP output per unit of construction land was evidently lower than that in the YRD urban agglomeration. The higher population density of the BTH agglomeration indicated that its demographic development was more compact than that of the YRD, whereas the lower GDP output per unit of construction land in the BTH region implied that its economic development was less intensive than that of the YRD. Thus, a comparison of the ULUE values of different urban agglomerations requires a full consideration of land use performance from different aspects rather than from single aspects. Additionally, the ULUE values of urban agglomerations in China were also scale dependent, indicating that inequalities among subregions cannot be identified solely through aggregate-level ULUE assessments of urban agglomerations. Thus, only five of the 13 cities in the BTH urban agglomeration had population densities higher than the values obtained at the aggregate level, and two of the cities had GDP outputs per unit of construction land higher than the values obtained at the aggregate level. By comparison, the population densities and GDP outputs per unit of construction land in the YRD urban agglomeration were higher than the aggregated values for these dimensions in 13 cities (half of all the cities) and 11 cities (42.3% of the total), respectively. Considering only the aggregated values of the ULUE of urban agglomerations could therefore lead to overestimations of the land use performance of large parts of the cities. Larger differences in the aggregate value and the average and median values are associated with a higher degree of unreliability of an assessment of urban agglomerations' overall performance. Hence, the ULUE of BTH at the aggregate level in terms of GDP outputs per unit of construction land was less reliable compared to that of YRD, while the ULUE of BTH at the aggregate level in terms of population density per unit of construction land was more reliable than YRD. By contrast, the median value of the ULUE of cities within the urban agglomerations was found to reflect their land use performance more accurately because these values were more representative of the majority of cities within the urban agglomeration.

4.2. Multi Factors Driving the Development of Construction Land in Urban Agglomerations

We found that land development patterns in the BTH and YRD urban agglomerations were affected by local as well as regional factors. For example, regional topographical factors, such as elevation and slope, significantly constrained the development of construction land in both urban agglomerations. The negative relationship between the development of construction land and its distance to a water body in the YRD indicated that the network of waterways promotes the development of nearby construction land. Therefore, stringent land use regulations and standards for areas located near waterways would help to promote ULUE. Moreover, the distribution of land along the coastline evidently affected land use. The occurrence of construction land in the BTH region was positively related to the distance from the coastline, whereas the development of construction land in the YRD was negatively related to the distance from the coastline. Thus, the coastal zone in the YRD appears to be exploited to a greater degree than that in the BTH region. Intensifying land use in the coastal zone of the YRD could increase the overall regional ULUE.

In addition to the physical regional drivers, human-induced regional factors had evident effects on the spatial development of construction land. Close linkages between major transportation networks, such as highways and high-speed railways, with spatial occurrences of construction land in both the BTH and YRD regions was a particularly striking finding. Greater proximity of an area to these major transportation routes corresponded to greater allocations of construction land, suggesting that the rapid development of a major transport network across the BTH and YRD regions would spur the development of construction land in their vicinities. The interactions between the transportation network and land use have been widely recognized in many studies [32,44,45]. For example, in Japan, the development of the high-speed railway network positively affected regional economic productivity because transportation accessibility enables flows of people and capital and improves connections among cities [46]. Moreover, the core urban areas of cities within urban agglomerations were found to influence the development of construction land in remote areas from a distance, particularly surrounding rural areas, which comprise a large proportion of China's urban agglomerations. Furthermore, dominant cities in both the BTH and YRD regions influenced the development of construction land in other cities, suggesting that these cities have a spillover influence across the entire urban agglomeration. A major factor accounting for spillover effects was the relocation of land-intensive enterprises from areas where land resources are in short supply to areas with abundant land resources. Given the abundance of land resources in the areas of relocation, their ULUE values were relatively low, resulting in a decrease in the overall ULUE of the entire urban agglomeration. This view is supported by empirical evidence provided in some studies. In a comparison of core urban and rural areas, Li et al. (2019) showed that land sprawl was more prevalent in rural areas than in core urban areas. In addition, non-dominant cities have more construction land sprawl than dominant cities [29]. Therefore, promoting the land use efficiency of non-dominant cities and rural areas will contribute to improved ULUE of the entire urban agglomeration.

Local (city level) factors also had significant impacts on land use, but these impacts varied among urban agglomerations. For example, in the BTH region, the development of construction land was negatively related to the proportion of the cities' tertiary industrial sectors, suggesting that intensive land use constitutes the growth mode of tertiary industry. Therefore, promoting the growth of tertiary industry in the BTH region would contribute to the intensification of land use, thus improving ULUE [4,15]. Conversely, in the YRD, the development of construction land was found to be positively related to the proportions of secondary and tertiary industries, indicating that the growth mode of these industries are mainly dependent on land resource inputs in this region. Therefore, transforming the land-extensive economic growth mode into a land-intensive growth mode would result in the improved ULUE of the YRD. Finding effective ways of mitigating the pressure exerted by economic growth on land resources in China's urban agglomerations is imperative, given the importance of advancing the country's economic development.

In sum, the occurrence of construction land in two major urban agglomerations in China was shown to be interactively affected by factors at both the city and regional scales. Hence, policy and decision making that targets a single spatial scale cannot be fully effective in promoting overall land use performance across an entire city-region. Unifying the land use standards of different cities across urban agglomerations could prove effective in reducing the inconsistencies between ULUE at aggregate and individual city levels.

5. Conclusions

The question of how different dimensions of a large-scale urban agglomeration and the disparities between its subregions can be incorporated into assessments of their performances poses a significant challenge for achieving synergetic sustainable development. In this study, we developed a new analytical framework for comprehensively measuring the ULUE of urban agglomerations that incorporated different dimensions and scales. Applying this framework, we found that the ULUE of two advanced urban agglomerations in China varied considerably; they were not only context dependent but were also scale dependent. The factors driving land development were trans-scale, encompassing local and regional factors. Our framework contributes to expanding the emerging literature on land use performance assessments in urban agglomerations conducted from various angles. Our findings may contribute inputs that could lead to the optimization of land use planning and management to enhance intensive land use, leading to improved ULUE. The framework could be applied in other urban agglomerations within and beyond China, particularly in rapidly developing countries and other countries evidencing fast-paced expansion of large-scale urban agglomerations with associated problems of land sprawl.

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