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Quantifying the Spatiotemporal Patterns of Urbanization along Urban-Rural Gradient with a Roadscape Transect Approach: A Case Study in Shanghai, China

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Abstract: Quantifying the landscape pattern change can effectively demonstrate the ecological progresses and the consequences of urbanization. Based on remotely sensed land cover data in 1994, 2000, 2006 and a gradient analysis with landscape metrics at landscape- and class- level, we attempted to characterize the individual and entire landscape patterns of Shanghai metropolitan during the rapid urbanization. We highlighted that a roadscape transect approach that combined the buffer zone method and the transect-based approach was introduced to describe the urban-rural patterns of agricultural, residential, green, industrial, and public facilities land along the railway route. Our results of landscape metrics showed significant spatiotemporal patterns and gradient variations along the transect. The urban growth pattern in two time spans conform to the hypothesis for diffusion–coalescence processes, implying that the railway is adaptive as a gradient element to analyze the landscape patterns with urbanization. As the natural landscape was replaced by urban landscape gradually, the desakota region expanded its extent widely. Suburb areas witnessed the continual transformation from the predominantly rural landscape to peri-urban landscape. Furthermore, the gap between urban and rural areas remained large especially in public service. More reasonable urban plans and land use policies should push to make more efforts to coordinate urban-rural development. This study is a meaningful trial in demonstrating a new form of urban–rural transects to study the landscape change of large cities. By combining gradient analysis with landscape metrics, we addressed the process of urbanization both spatially and temporally, and provided a more quantitative approach to urban studies.

Keywords: urban-rural gradient; spatiotemporal patterns; landscape metrics; a roadscape transect approach; rapid urbanization; Shanghai

1. Introduction

Urbanization is the process by which the natural landscapes, such as forest and agriculture, are replaced by man-made elements which are mainly impervious surfaces and artificial structures [1]. During the past decades, large cities in China had accelerated their urbanization rate, resulting in multiple changes in the spatial pattern and structure of original landscapes [2,3], which profoundly alters the sustainability of ecosystems far beyond the cities themselves [4]. Since the 1980s, the Chinese economic reform, marketization, and globalization combined to bring about new forms of settlements and new processes of urban–rural nexus [5]. The peri-urban landscape created by this transformation, characterized by various land uses, varied its number, density, size and shape to a highly fragmented and complicated form [6]. Furthermore, the speed, growth modes, and landscape pattern of urbanization are broadly related to each other. Hence, integrated studies focused on both human and natural systems is necessary in illustrating these complex systems and processes [7]. Thus, quantifying the urbanization patterns and the ecological processes in a spatial and temporal perspective is a key point to solve the societal, economic and environmental problems [4,8,9].

The recent rapid urbanization taking place in east Asia has exhibited a process that is distinctly different from that of the Western developed countries. This has contributed to the emergence of desakota which is characterized by an intense mix of agricultural, industrial, residential and other land types that are distributed between urban cores and rural areas [10,11]. From an economic, environmental and social viewpoint, the desakota region represents an intricate space that relies on the mutual dependence of both cities and rural areas [8]. Scholars suggested that understanding the rural–urban nexus and this new landscape pattern is a key to realize China's tremendous social and economic transformation [12,13].

Urbanization gradients are indirect and complex [14], the regional urbanization is partly determined by its proximity to the urban center [15]. Since McDonnell and Pickett [16] proposed a framework that provided a hierarchical approach to detect the multiple environmental changes associated with urbanization, the urban-rural gradient approach has been widely applied in urban landscapes ecology for describing the landscape pattern changes caused by rapid urbanization around the world [14,17]. Integrating ecological, social, and physical factors, the GIS-based gradient methods have proved to be powerful tools for exploring spatiotemporal dynamics and the ecological consequences of urbanization [8,18]. In previous studies, although the urban–rural gradient was identified and investigated widely, the main focus was on the spatiotemporal patterns of the ongoing urban growth and sprawl. McDonnell and Hahs [14] pointed out that few studies addressed the importance of transect selection itself. Despite this, the gradient approach has made a significant contribution to our understanding of the ecology across urban and rural landscapes. More specific measures can be used to gain mechanistic understanding of spatiotemporally ecological progress responses to urbanization gradients.

Anthropogenic gradients can be indirectly used to evaluate the response to changes in landscape characteristics [19]. As the spatial determinants of urban expansion and a transport system that interacts with surrounding landscapes, road networks can significantly disturb the ecological flows, spatiotemporal patterns of urban expansion, and settlement distribution [20,21]. Since the roads exerted intense influences on landscape patterns [22], they can serve as indicators of urbanization intensity. In China, railways played an important role in the economic development and urban construction during past decades, and as a result it can indicate the urbanization intensity to a certain extent. Furthermore, railways are the only type of road that run straight through the urban center, because the accessibility to urban core is one of the most striking and important factors to be considered in designing railway routes. Due to its unique characteristics, the roadscape transect approach, which indicates the landscape pattern changes along railway routes, can serve as a potential measure of urban gradient analysis.

To better illustrate the urban landscape patterns and their impacts on the environment, a wide range of approaches, like the applications with landscape metrics and remote sensing data, have been widely used in urban studies [14,15,23,24]. Dietzel et al. [25] pointed out that metrics refer to different ecological significances, and vary in performance according to land use types during an alternating urbanization process of diffusion and coalescence. Researchers should select appropriate metrics depending on their research objectives. Based on this, the study will provide a new interesting paradigm in urban morphology, especially from a comparative perspective of landscape patterns. In order to bring the public's attention to societal and eco-environmental consequences of the rapid urbanization, the purposes of this study are threefold: (1) methodologically, to test whether the gradient analysis with landscape metrics along the railway route can be an effective approach in detecting the characteristics of urbanization pattern; (2) theoretically, to summarize the general temporal and spatial trends of the individual and entire landscape patches change, and the characteristics of landscape metrics along an urban-rural gradient with the rapid urbanization; and (3) practically, to provide the suggestion and implications for urban land-use planning in dealing with the consequences of rapid urbanization, such as desakota pattern and urban-rural separation. Superior to the previous studies about urban–rural gradient detection and development of city, this study emphasized the urbanization process of individual and entire landscapes in both spatial and temporal pattern, and focus on the landscape patterns from the urban core to rural areas with a gradient along the railway route.

2. Study Area

With a residential population of over 20 million and total land area over 6300 km^2, Shanghai is located on the east coast of China, with Jiangsu and Zhejiang province being its northwestern and southwestern neighbors respectively (Figure 1). As a central city of Yangtze River Delta Urban Agglomeration, Shanghai and its suburbs were selected as the study area. By using spatial analysis along railway route through the city, the authors attempted to describe the urbanization intensity and patterns towards different direction from the city center along an urban-rural gradient.

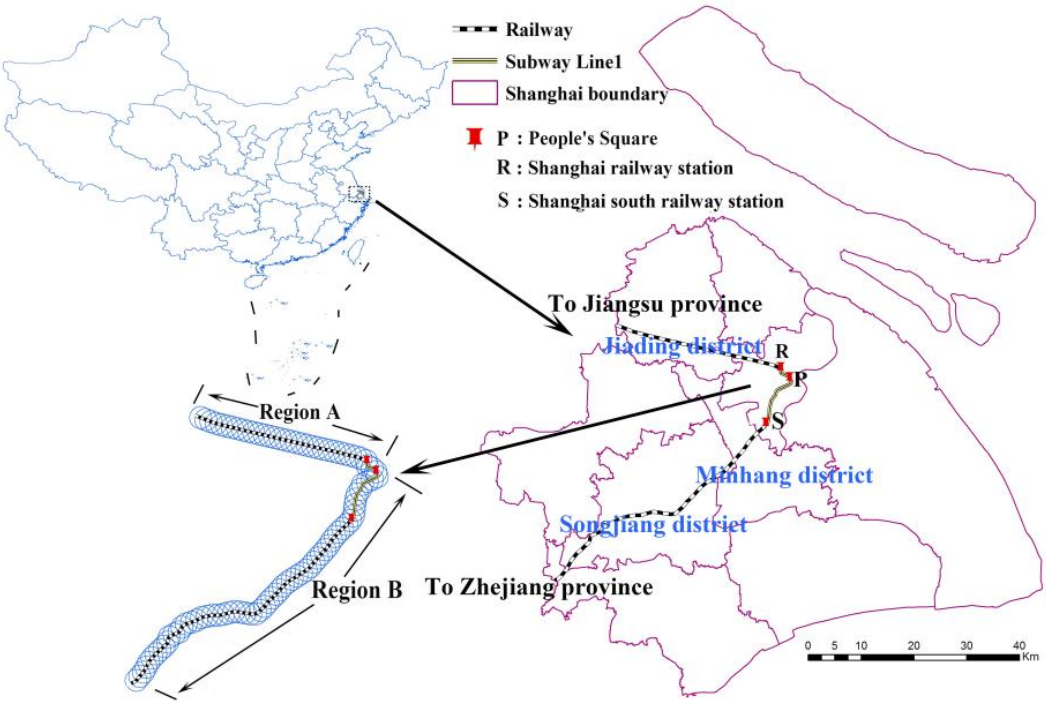

Figure 1. The location of shanghai city and the transect belts along the railway route.

Shanghai–Nanjing–Hangzhou urban agglomeration in China's lower Yangtze Delta is widely known as the desakota regions defined by McGee–Ginsburg model [10]. Relying on the hinterlands of the Yangtze River Delta, the richest area in China, Shanghai has been the most important center for manufacturing, commerce, and international trade with the urban area increasing from 91.5 km^2 in 1947 to more than 1300 km^2 in 2010. With an urbanization rate approaching 90% in the 2010s, Shanghai has experienced unprecedented economic growth and land transformation [26]. However, the desakota pattern of Shanghai was most prominent after the 1990s because of rapid regional urbanization due to the establishment of the Pudong New Area [11]. As a whole, Shanghai could serve as a representative site to explore the generality of desakota pattern to better recognize the spatiotemporal changes of urbanization of metropolitans in China.

3. Data Preparation and Methods

3.1. Land Use/Land Cover Data Preparation

Land use data was acquired based on a time-series of false-color infrared aerial photos acquired in 1994, 2000 and 2006, respectively. These aerial photos were georeferenced to the WGS84 coordinate system and were mosaicked to cover the whole study area. Based on the digitized aerial photos, the vector land use dataset was drawn by visual interpretation using ArcInfo GIS 10.0 [27]. The land use type was classified into eight classes as below (Figure 2): agricultural land (AL), industrial land (IL), green land (GL), residential land (RL), public facilities (PF), transportation (TR), water (WA) and unused land (UL). Finally, the vector data was converted to raster with a 10 m × 10 m spatial resolution. The map of railway and subway Line 1 at the scale of 1:100,000 were provided by the Shanghai Bureau of Surveying and Mapping in ARCGIS shapefile format. All the data layers were georeferenced to the same coordinate system.

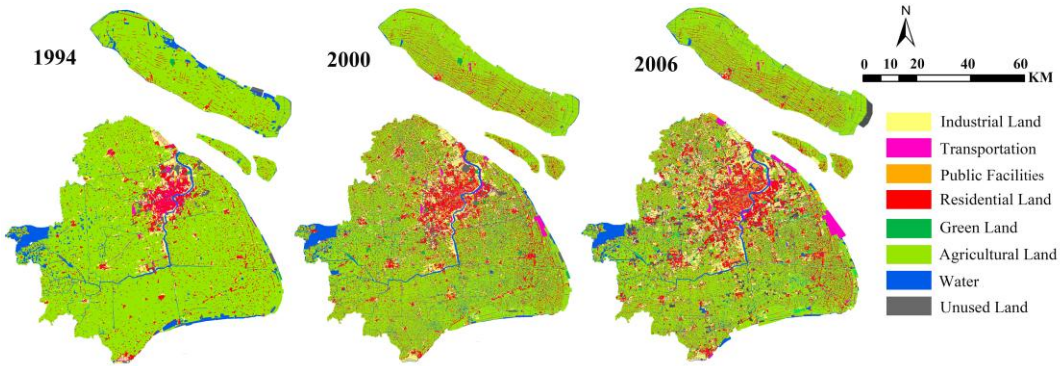

Figure 2. The land use map of Shanghai metropolitan region.

3.2. The Urban-Rural Gradient Transect along the Railway Route

Recently, scholars have attempted to propose a variety of measurements to describe the spatiotemporal landscape pattern changes caused by rapid urbanization. There are two commonly used ways to implement an urban–rural gradient analysis. One is buffer zone method, with which landscape metrics are derived for a series of concentric circles with the urban core as their centers [15,28]. The other is transect-based approach, landscape metrics are calculated along a transect which is delineated from the urban center to rural area [8,23]. However, both of the two measures have their own advantages and disadvantages.

Taking into consideration that the railway is nearly a linear element, we designed a measure that synthetically combined the transect-based approach and the buffer zone method (Figure 1). The Peoples' Square, which is the economic and political center of Shanghai city, was set as the urban center. The total length of the railway and subway Line 1 involved in this study, as calculated within a GIS software, amounted to nearly 96 km. Shanghai railway station and South Shanghai railway station were connected with Peoples' Square by the subway Line 1 in the urban area. The whole study area was made up of two parts: the area near the Suzhou city (belonging to Jiangsu Province), mainly the Jiading district ("Region A" in Figure 1); and the area close to Jiaxing city (belonging to Zhejiang Province), mainly the Minhang and Songjiang district ("Region B" in Figure 1). Similar to moving averages, points along the railway were selected at a constant interval *d*. Circular buffer of these points were also made with a radius *d* in order to smooth the noise caused by local variations. Preliminary experiments were made with given d values from 1 km, 2 km to 10 km respectively and finally the 3 km tested to be the adaptive scale for *d* in our analysis. With this method, 32 overlapping circular samples were generated to calculate the landscape metrics along the gradient without restrictions from the administrative boundaries.

3.3. Landscape Metrics

To quantify the changes in landscape patterns along the railway, landscape- and class-level metrics were implemented to capture the synoptic features. Landscape metrics used in ecological studies focused mainly on size, density, shape, edge, connectivity, diversity, etc. The redundancy and overlap among landscape metrics is common [29], so not all of them were needed as the indicators of landscape composition and configuration. Based on previous research [4,30] and the pre-experiments incorporated in correlation with analysis among metrics, seven landscape-level metrics (PD, ED, SHDI, LPI, LSI, AI and CI) and seven class-level metrics (CA, PD, ED, AI, LSI, LPI and CI) were adopted (Table 1). All the calculation were conducted under the software FRAGSTATS 4.0 [31] based on the LULC data acquired from the aerial photos. By doing this, the authors tried to describe the landscape pattern changes along the railway from rural area to urban center.

Table 1. The landscape metrics and their descriptions (L: landscape level, C: class level).

Landscape Metrics (Abbreviation)	Study Level	Description
Aggregation index (AI)	L, C	AI represents the aggregation of the landscape pattern.
Class area (CA)	C	The area of the landscape patches (100 ha).
Connectance index (CI)	L, C	It is defined on the number of functional joinings between patches of the given types.
Edge density (ED)	L, C	It equals the total length of the landscape patch edges divided by the total landscape area (m/ha).
Landscape shape index (LSI)	L, C	Total length of the patch edges divided by the total area of the landscape (m/m^2).
Largest patch index (LPI)	L, C	The percentage of the largest patch in the total landscape (%). It refers to the dominance for one type of patch.
Patch density (PD)	L, C	The numbers of patches per 100 ha.
Shannon diversity index (SHDI)	L	High value of SHDI means the type of patch increased or each type of the landscape is more equitably distributed.

4. Results

4.1. Synoptic Characteristics of the Landscape Patterns from 1994 to 2006.

At the landscape level (in Figure 3), PD, ED and LSI increased explosively in T1 and have a slightly decrease during T2 (the T1 refers to 1994–2000 and T2 refers to 2000–2006). This trend was consistent in both Region A and B, indicating that more fragmented, unstable and irregular landscapes increased dramatically with the accelerating spread of urbanization across the Shanghai metropolitan. The homogeneous natural landscape altered resulted in smaller, highly fragmented patches of land. SHDI increased progressively in T1 and T2 due to their more even distribution and heterogeneity of the landscapes. These four metrics can be used as representative indicators to illustrate the synoptic characteristics among the landscape metrics. Therefore, the whole transect was in a diffusion process in T1, while obvious characteristic of the coalescence process were exhibited in T2. In general, T1 refers to the rapid urbanization without strict supervision of government land policy, and T2 refers to the period that government slows down the construction of urban settlement in an attempt to optimize both the use of resources and urban plans. Due to the large cover of the cases, the results of region A and B showed similar patterns in two time intervals, especially for AL and RL. In order to explore the comparisons between the two case areas, a finer scale along the gradient must be taken into consideration.

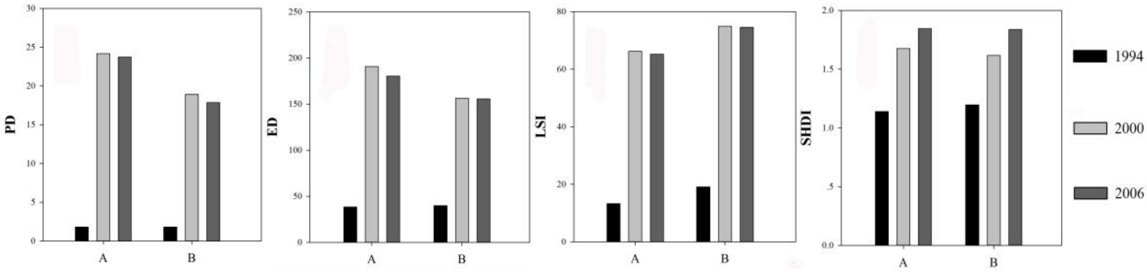

Figure 3. Synoptic characteristics of the landscape metrics in the transect at landscape level from 1994 to 2006 (A: Region A; B: Region B).

Because there was very little available data for both the water body (WD) and unused land (UL) along the gradient, and the railway was incorporated in the transportation land (TR), these three types were not considered in our test. The other five kinds of landscape, residential land (RL) (Figure 4a), agricultural land (AL) (Figure 4b), industrial land (IL) (Figure 4c), green land (GL) (Figure 4d), and public facilities (PF) (Figure 4e) showed specific trends and patterns individually. The residential land (RL) doubled in area from 1994 to 2006 in both region A and B, while the area of industrial land (IL), public facilities (PF) and green land (GL) all increased by several times, due to the occupation of more than half of the agricultural land (AL) during this period. In general, the PD, ED and LSI of IL, GL and PF showed similar patterns, with a low value in 1994 and a progressive increase in T1 and T2. However, the PD, ED and LSI of AL and RL had peak values in 2000 and exhibited decrease trends in T2 after the exponential growth in T1. The result revealed that changes of IL, GL and PF are not synchronized with that of AL and RL in the urbanization process. In both region A and B, the LPI of IL and AL decreased gradually, whereas the LPI of RL decreased first in T1 and then increased in T2. For the LPI of PF and GL, there was a slightly different trend. The value in Region A decreased gradually, whereas the value in Region B decreased from 1994 to 2000 and then increased from 2000 to 2006. The new patches of public facilities and green land emerged and aggregated into large ones. The CI of GL and AL decreased during two time intervals, indicating that the lower connectivity weakened the function of their ecological services for the city.

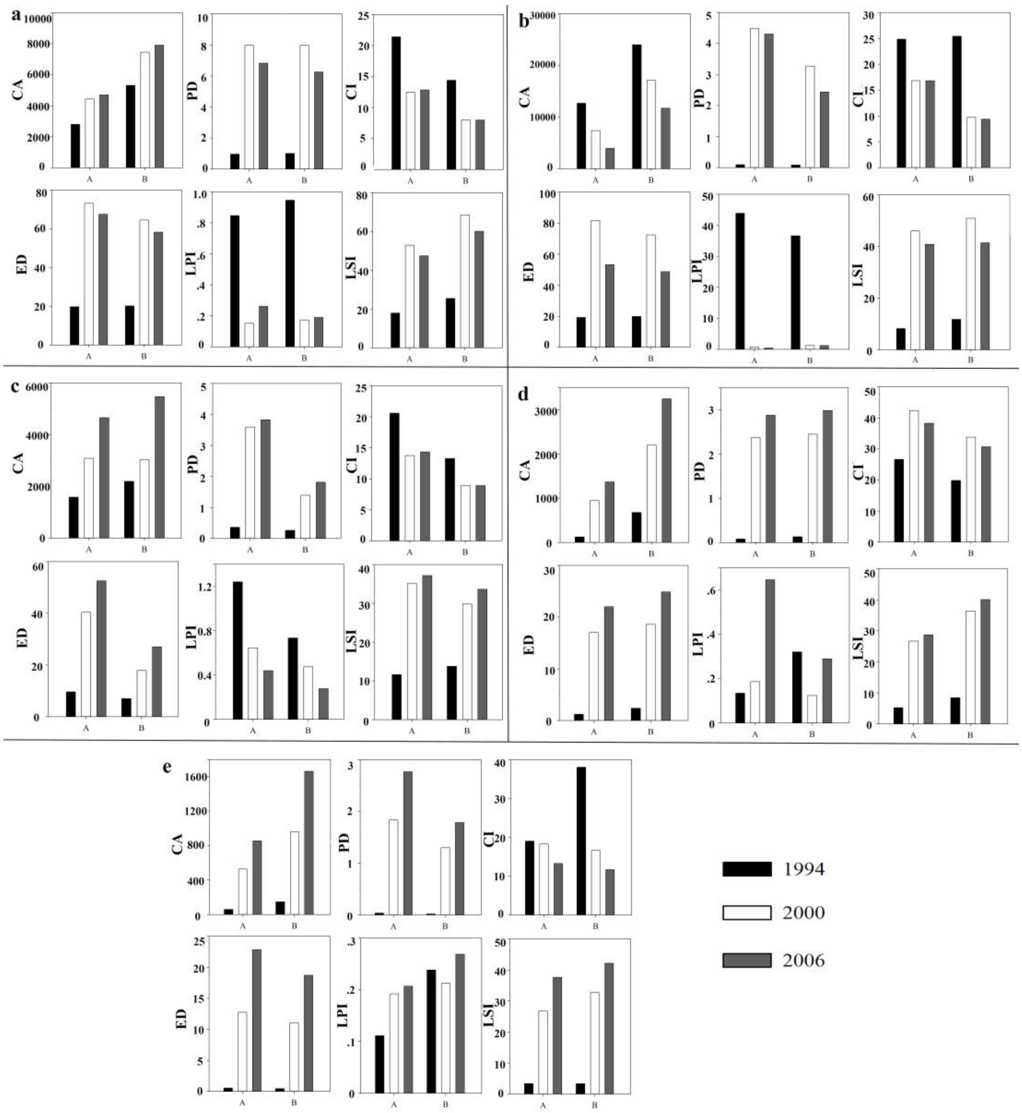

Figure 4. The landscape characteristics of individual land use type from 1994 to 2006 ((**a**) residential land; (**b**) agricultural land; (**c**) industrial land; (**d**) green land; (**e**) public facilities; A: Region A; B: Region B).

4.2. The Characteristics of Landscape-Level Patterns along the Urban-Rural Gradient

In Figure 5, the horizontal axis with value 0 indicates the location of the urban center (The People's Square), wherever the northwestern and the southwestern locations possess negative and positive values indicates their distance to urban center along the railway route. Several locations along the gradient needed to be illustrated: Anting town with the largest population in Jiading district (−33 km), Shanghai railway station (−3 km), Shanghai South railway station (+11 km), the administrative center of Minhang district (+20 km) and the administrative center of Songjiang district (+37 km). The metrics at landscape-level showed significant spatiotemporal patterns and gradient variations along the transect (Figure 5). The PD, ED and LSI with the largest value in the urban center and two-peak pattern in 2000 and 2006, exhibited increasing trends from 1994 to 2006 along the gradient. However, AI exhibited close to an opposite spatial pattern in comparison to PD, ED and LSI. Dietzel et al. [25] pointed out that PD, ED and LSI would increase with urbanization, while AI would decrease due to the coalescence of adjacent patches. These results suggested that the landscape, as a patch mosaic, became more fragmented, irregular and unstable with urbanization. Multiple-peak patterns and a fluctuating trend were found for SHDI and CI. A low CI value with the high SHDI value in Jiading, Minhang and Songjiang (around −15 km , +20 km, +37 km) illustrated the dominant patch types (mainly the residential and industrial land) with low connection and high diversity. Anting town (around −30 km), the linkers between Jiangsu and Shanghai, developed rapidly since the 1990s, with its SHDI increasing and CI decreasing. Refer to Sui and Zeng [11], the landscape pattern changes and excessive land conversion in these areas were distinctly consistent with the typical description of desakota pattern. As a whole, the landscape patterns of the urban center matched the three steps according with the urbanization theory, On the other hand, the suburbs (Jiading, Minhang and Songjiang) exhibited a diffusion process with steady-state growth in diversity and fragmentation during the whole study period.

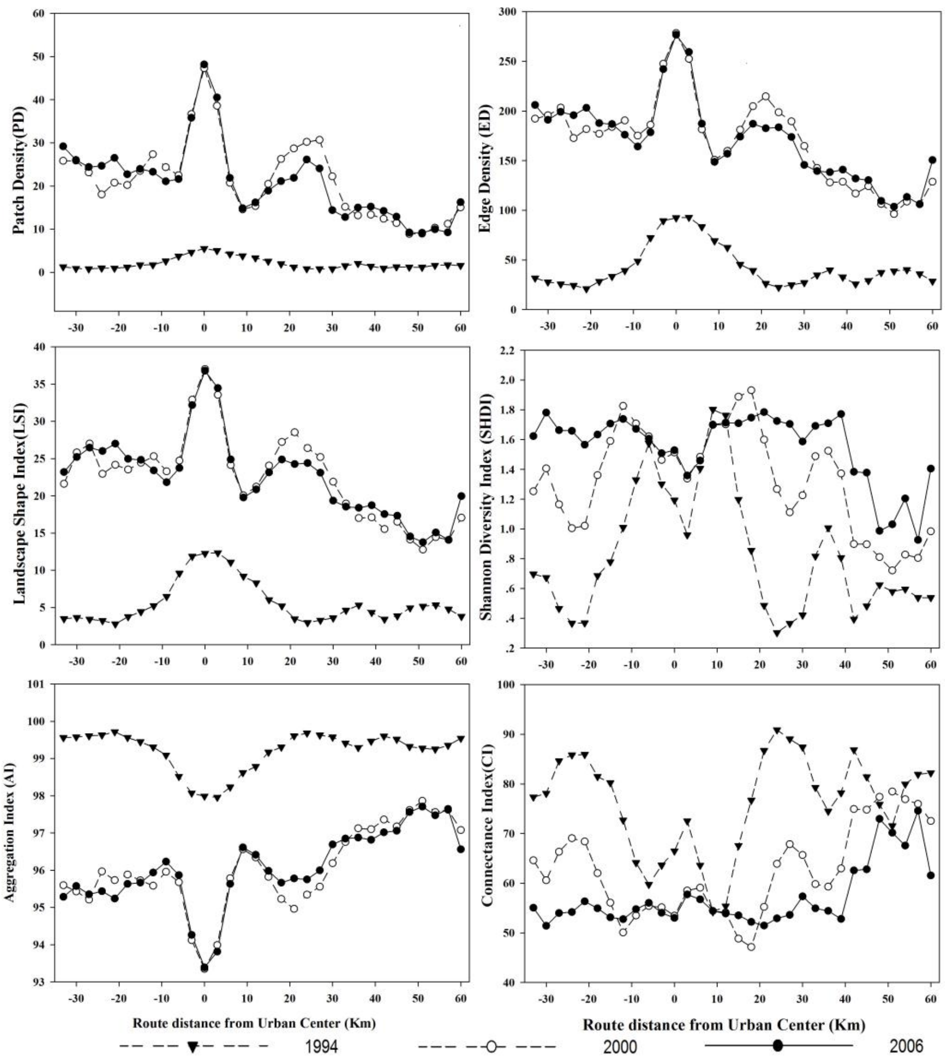

Figure 5. Landscape pattern metrics at landscape level along the transect across Shanghai metropolitan.

4.3. *The Gradient Analysis of Landscape Patterns with Class-Level Metrics along the Railway*

To further clarify how the spatiotemporal pattern of urbanization changed, class-level landscape metrics were employed to quantify individual land use type along the gradient. The growth of residential land (RL) is one of the most distinct characteristics in the process of urban development in Shanghai. The values of CA, ED, PD and LSI increased monotonically from fringe to the suburbs, and finally peaked in the city center (Figure 6). However, the changes of CA, ED, PD and LSI are not synchronized temporally. CA steadily increased in both T1 and T2, but the other three metrics had the largest value in 2000, exhibiting a slightly decrease in T2. PD, ED and LSI of RL were first increased, and then decreased during the two time span. This may be because the old residential homes were rebuilt after demolishment during the urban renewal, which led to more dominant and compact distribution for RL. In T1, PD, ED and LSI increased dramatically along the whole transect, indicating the diffusion of urbanization. This was mainly due to the appearances of large new residential patches. However, the urban core areas and the suburban areas demonstrated coalescence characteristics in T2, especially at the location from −20 km to +20 km. LPI exhibited multiple peak pattern in city and suburbs in 1994, with great fluctuation in the gradient belt. In comparison to LPI, AI showed a gentle trend of change. Low LPI combined with high AI in suburbs indicated that residential patches are well separated from each other, with more scattered distribution in space. These two metrics had the largest values in 1994 and decreased gradually as the urbanization progress went on, implying some reasonable plans and effectively measures for residential land had been taken to improve the low land-use efficiency due to loose distribution and uneven regional development. The landscape transect analysis results for RL can be used to test the hypotheses for the spatial configuration and composition dynamic of urban sprawl in different stages.

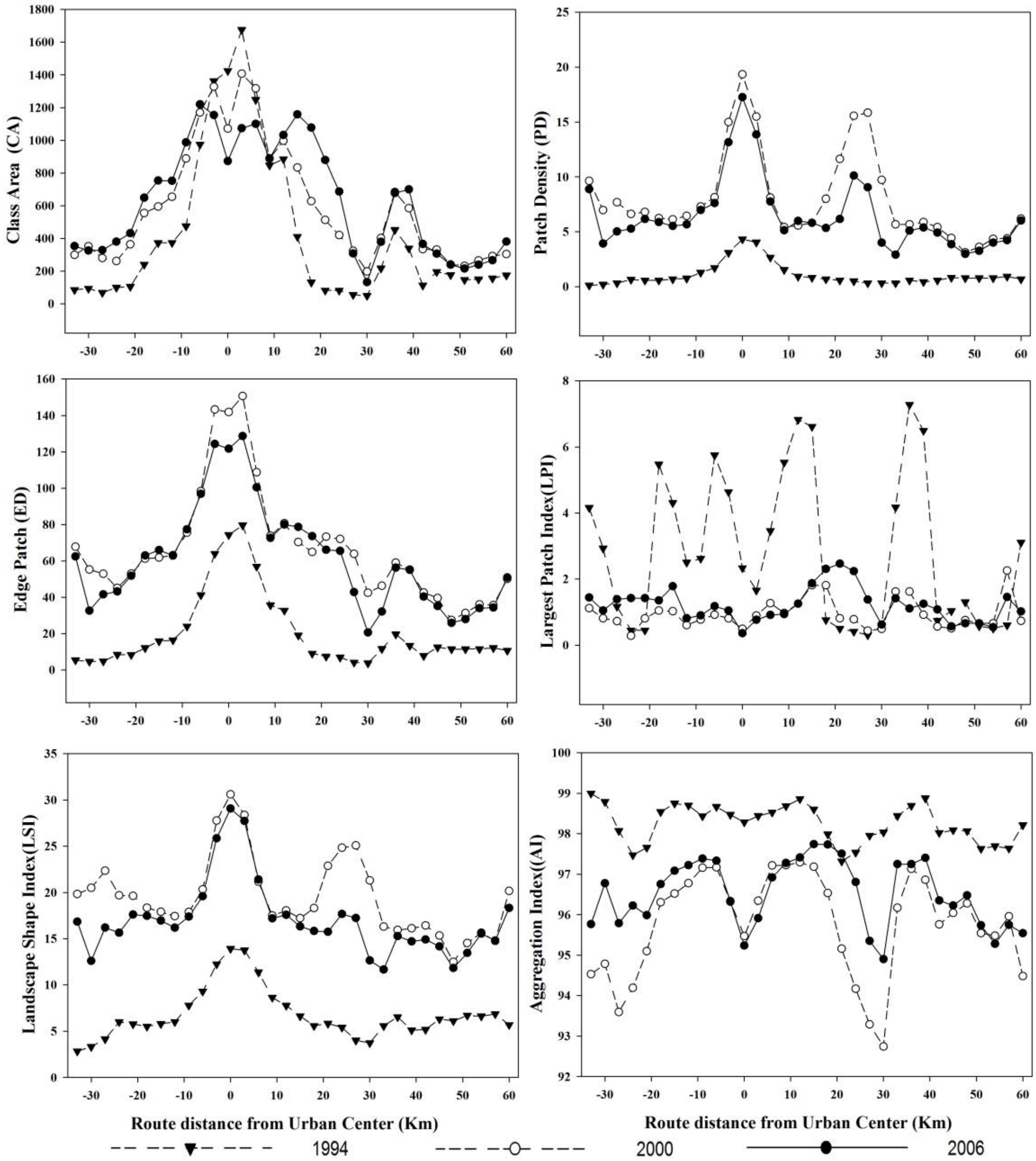

Figure 6. Landscape pattern metrics for residential land along the transect across Shanghai metropolitan.

For agricultural land (AL), less valid data was acquired in urban core area (Figure 7). Urbanization has decreased the area of agricultural land dramatically from 1994 to 2006, especially in suburban area. CA, PD, ED and LSI increased dramatically from the urban center to the suburbs and then decreased towards the city fringe along the gradient. As the residential land rose (an inverted U-shape pattern along the gradient), agricultural land fell (a U-shape pattern along the gradient), exhibiting a significant inverse relationship. The results illustrated a typical desakota pattern in the transition zone between urban and rural areas (−30~−20 km and 20~30 km) where the agricultural land area was gradually occupied by man-made systems. Considering the changes of landscape metrics, AI and LPI decreased dramatically in both T1 and T2, showing a fluctuating trend along the gradient. Similar to RL, the PD, ED and LSI changed synchronously during 1994–2006, with the highest and lowest values in 2000 and 1994 respectively. These three indices generally increased in T1, but decreased slightly in T2. The irregularity, fragmentation and shape complexity of agricultural land showed a trend of rise to decline. One explanation for this is may be that the shrinking farmland with high fragmentation was occupied and disappeared with the urbanization course proceeding [32].

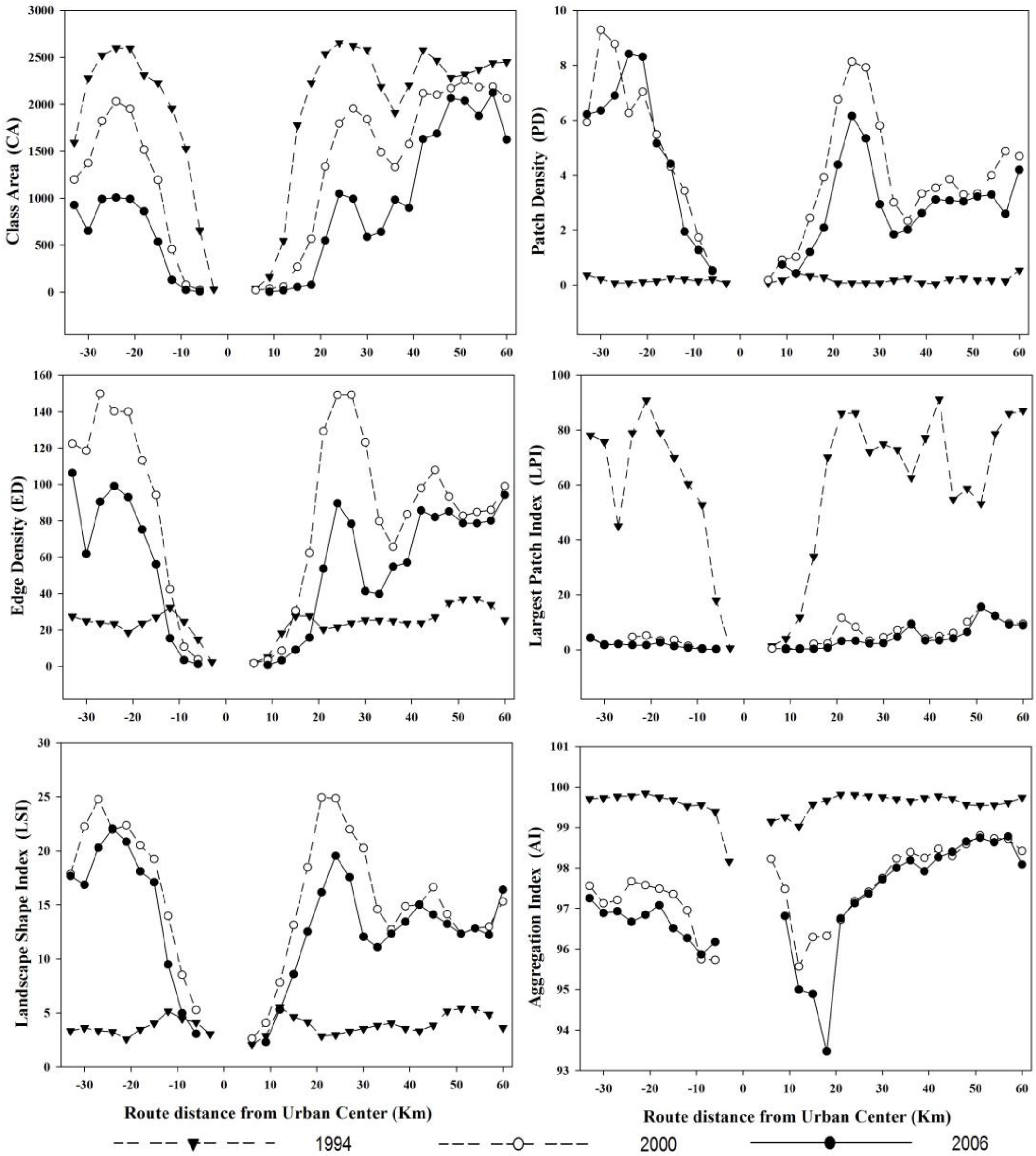

Figure 7. Landscape pattern metrics for agricultural land along the transect across Shanghai metropolitan.

According to the results of industrial land (IL), CA, PD, ED, LPI and LSI had the lowest value in the urban center and the largest value in suburbs (Figure 8). These metrics exhibited multiple peaks and a wave-like pattern along the gradient. It also showed the progressive diffusion of IL along the transect belt in rapid urbanization process. The area and density of IL experienced rapid increases during both T1 and T2, except for in urban core area. The increasing of IL in suburbs was partly due to the rise of rural and township enterprises, together with some medium and small-scale industrial parks, commonly with a high-speed urban expansion. Both LPI and AI had decreasing trends from 1994 to 2006. This might be due to the industries moving to suburban and rural areas after technology improvement, and formed a more decentralized distribution in space.

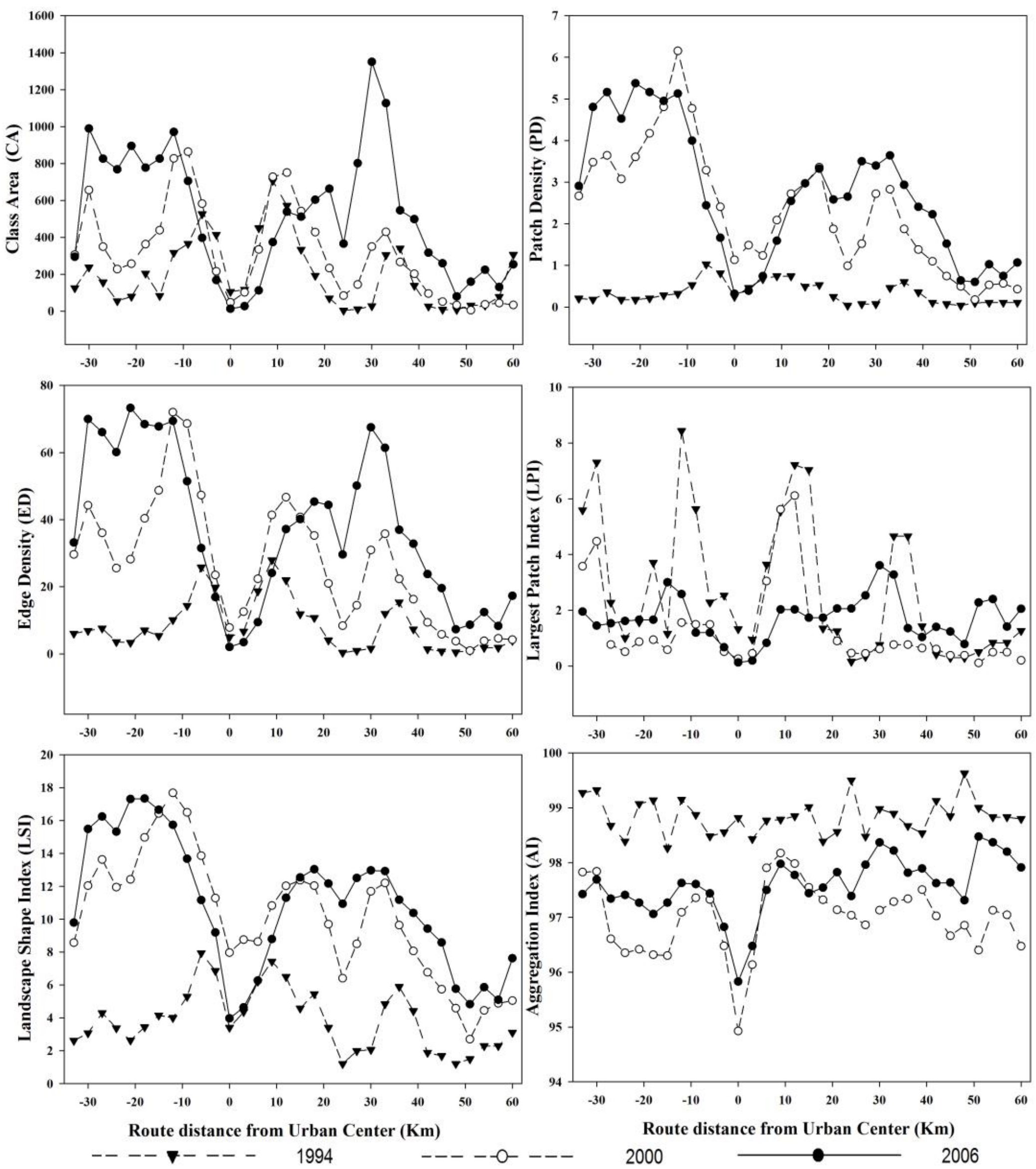

Figure 8. Landscape pattern metrics for industrial land along the transect across Shanghai metropolitan.

The public facilities (PF) exhibited one peak pattern in the urban center, the values of CA, PD, ED and LSI more than doubled in the location near the city center, and increased dramatically in T1 and smoothly in T2 (Figure 9). This is different from the results of Li et al. [28]. Since the PF were usually built close to the downtown, the gap between urban and rural in public service level increased. Although the city expanded its boundary, rose the population density and increased the demand of public facilities, the PF land increased slowly in rural areas during accelerating periods of urbanization. Compared with the rapid pace in downtown, the construction of public facilities is relatively backward in suburban and rural areas. The implementation of more reasonable policies for regional development in the context of urban-rural integration are urgent to put forward.

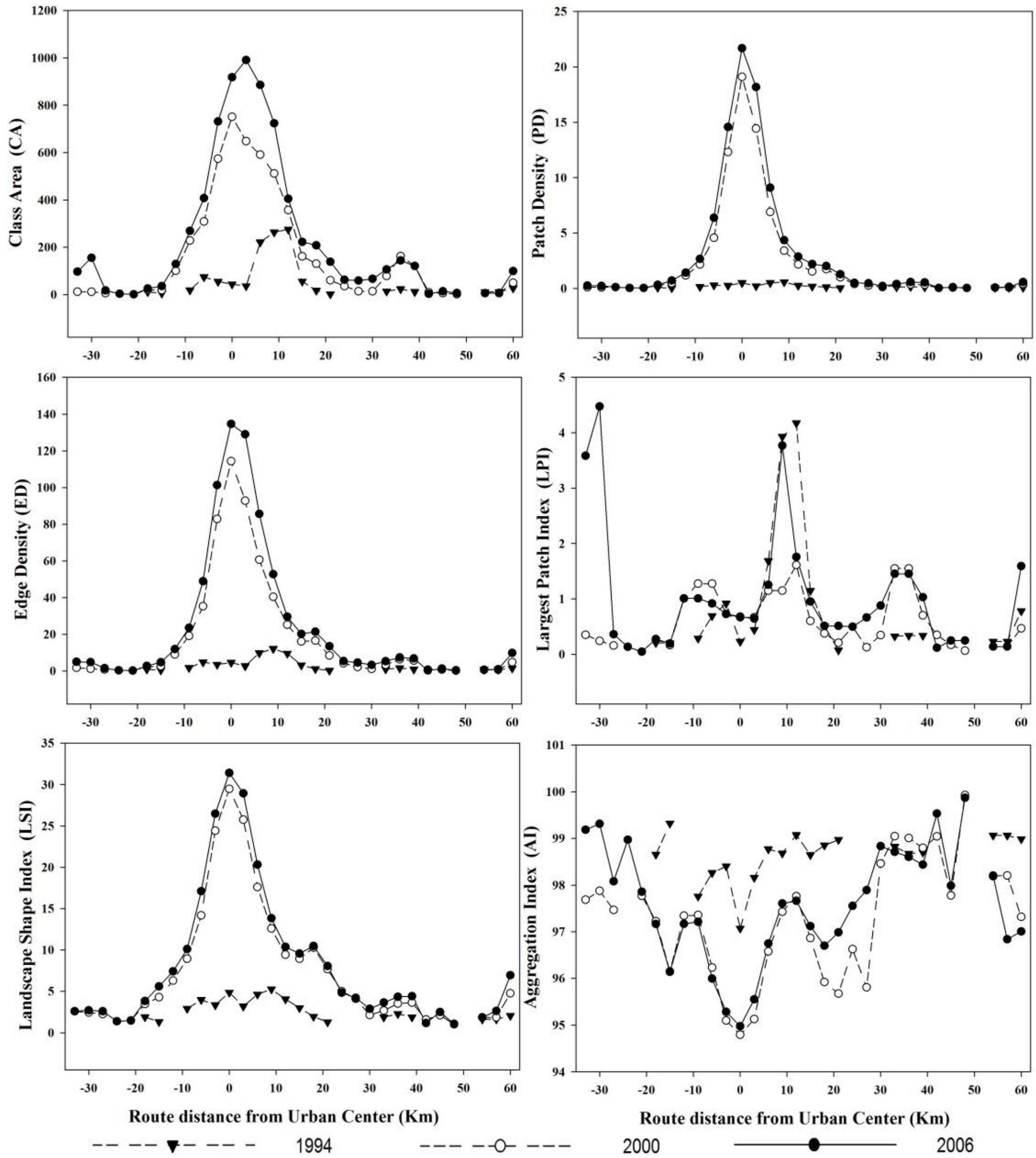

Figure 9. Landscape pattern metrics for public facilities along the transect across Shanghai metropolitan.

The metrics of green land (GL) also exhibited multiple peak patterns in 2000 and 2006, while continuous data was not acquired along the gradient in 1994 (Figure 10). This kind of approach to gradient analysis showed some limitations in determining spatiotemporal patterns of the land use type that are rarely distributed beside the road line. Since natural forest and grass were both scarce in Shanghai, green land mainly refers to the park, which was extensively planned after the new century. These metrics exhibited multiple peaks with largest value in center of city and satellite towns (around −15 km, 0 km, 20 km and 35 km) along the gradient. Meanwhile CA, PD and LSI all exhibited a rising trend over time. The urban center with high density green lands owing to the urban renewal, and natural and semi-natural green land in suburban area would be replaced by artificial green spaces gradually due to the satellite towns initiated plan by the Shanghai municipal government since 2000s.

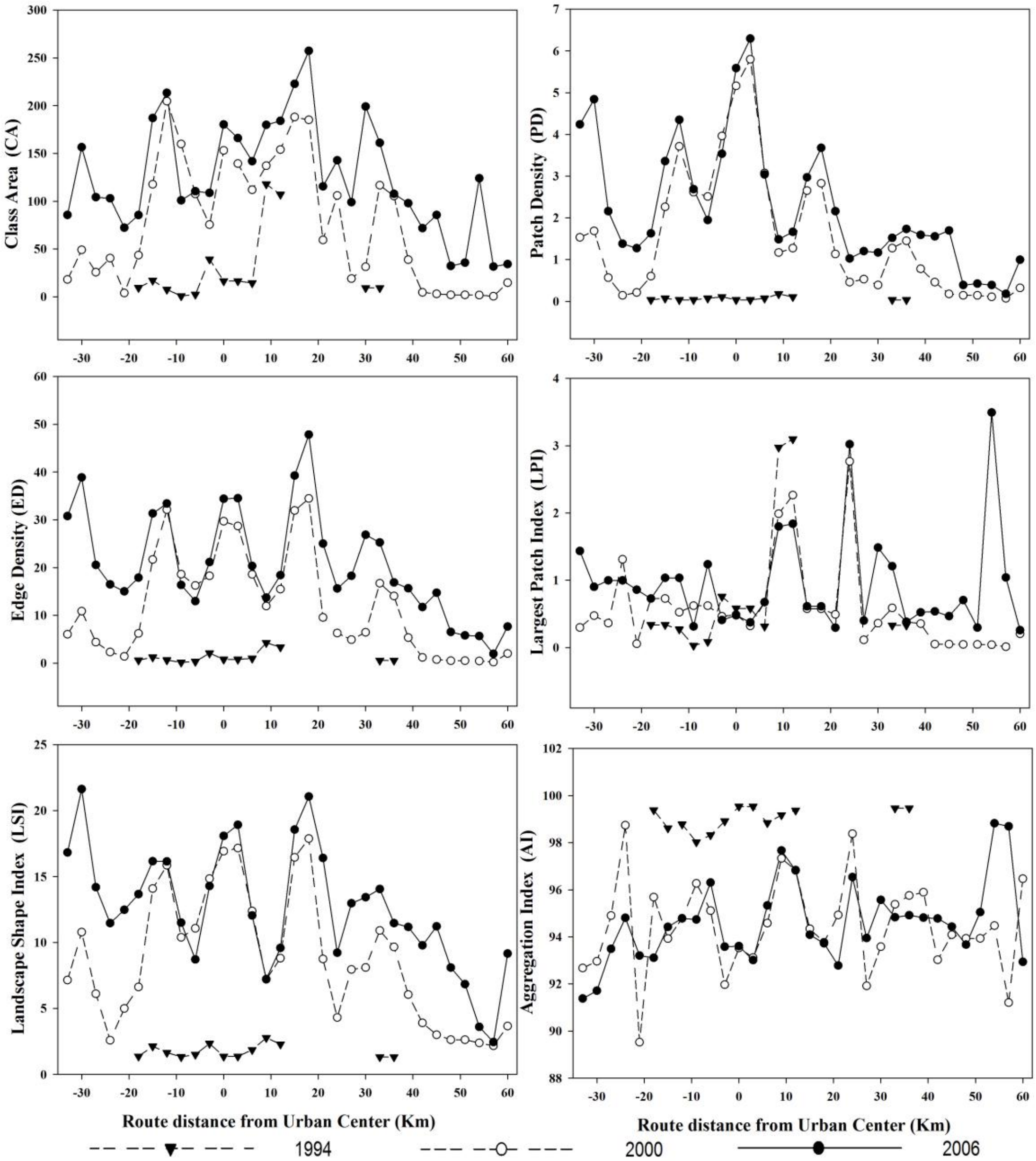

Figure 10. Landscape pattern metrics for green land along the transect across Shanghai metropolitan.

5. Discussion and Conclusions

5.1. The Metrics Varying Characteristics for Individual and Entire Landscape

In this study, landscape metrics are informative in distinguishing dynamics and patterns of LULC and varied their descriptive ability and sensitivity. Therefore, a group of meaningful metrics that can be applied in exploring spatial patterns and related temporal landscape changes, should be jointly applied to identify the characteristics of urbanization patterns.

The changes of CA, PD and ED, which are sensitive to land use change, habitually displayed similar spatiotemporal patterns and had exponential growth across the transect in the early stages of urbanization. Both ED and PD at class- and landscape- level decreased from urbanized areas to semi-natural landscapes, and finally fell dramatically within the intensive agricultural systems. The individual patches became increasingly irregular and fragmented, while the shape of the entire landscapes as complicated mosaics would be more irregular and fragmented with urbanization [4]. LSI in landscape level exhibited a parabolic tendency along the gradient. It was also relatively steady in the early urbanization stage, and then increased exponentially with rapid development. One explanation for this is that urbanization will result in many isolate patches with high fragmentation and low connection, and this trend will last until urbanization levels reach a certain degree [23]. These configurational metrics decreased progressively when the samples moving from human-made systems to the natural landscapes and temporally exhibited S-shaped curve during the urbanization period. Urban studies by scholars around the world have found these patterns to be overwhelmingly common [1,8,23,33].

As an indicator of the landscape diversity, SHDI exhibited a wave-like pattern moving from urban to the rural area, with a greater growth in suburbs than that in urban center (Figure 5). A hypothesis indicated that SHDI would increase until the landscape is highly urbanized and intensely heterogeneous [34]. Both high and low values of SHDI existed in urban areas. It is easy to realize that highly urbanized areas would be more homogeneous than developing areas. In contrast, indicating the aggregation and connection of the landscape, AI and CI uniformly decreased during the whole study period. This reflected individual patches that became more scatter and isolate due to urban development, which is consistent with former studies [24,35]. In regard to the majority of the land use types, LPI for RL, AL and IL showed high variance along the gradient, while higher values appeared in rural and urban center. The dominant species, such as AL in rural areas and RL in the urban core, steady decreased in the process of urbanization. As a whole, these compositional metrics displayed uniform changes in both of the two time stages, and exhibited slightly different patterns when compared to the configurational metrics.

5.2. The Spatiotemporal Pattern of Landscape Changes under Rapid Urbanization

Comparative and temporal analyses of landscape metrics reveal that the urban form of cities can change quickly with rapid urbanization. Previous studies reported that urban growth regularly exhibited a spatiotemporal pattern of U-shaped profile or a wave-like characteristic in response to the land use changes [28,36]. The outward wave-like patterns of peak values for metrics showed that the continuous spread of urban expansion made Shanghai city push its borders farther from its heartland. Meanwhile, the area with desakota pattern increased in magnitude during the study period. In this study, the spatial evolution of urbanization in the urban center can be described as a two-step process. A shift from diffusion to coalescence when the entire landscape became more compacted and heterogeneous, declined in shape complexity, and increased in diversity, which was characterized by the decrease of PD, LSI and SHDI. This distinct process confirmed the hypothesis proposed by Seto and Fragkias [3].

Moving towards the semi-natural landscapes, the satellite towns surrounding Shanghai's downtown, such as Jiading, Minhang and Songjiang, absorbed potential suburban development, and witnessed the continual transformation from the predominantly natural landscape to human-made landscape, in accordance with desakota pattern. Higher shape complexity in suburbs is associated with mixed landscapes dominated by residential and industrial land. This was due to their increase in human settlement and industrial investment since the Pudong development and opening up [37]. The landscape patterns in these areas showed increased PD, ED, LSI and SHDI, decreased CI, LPI and AI, which together indicated urbanization resulting in more irregular, scattered, fragmented, isolate, diversified and heterogeneous landscape in suburbs of Shanghai. The results were consistent with Forman and Godron [38], which stated that along a landscape modification gradient patch density and shape would increase, meanwhile landscape connectivity would decrease with urbanization. The results of LPI implied that the residential and industrial land occupied most portions of landscape area within the rural-urban fringes, where natural landscape were originally dominated by agricultural and green land [33]. Highly mixed landscape emerged in suburbs due not only to the "top-down" forces from urban center, but the "down-top" influences exerted by suburbanization from rural industrialization as well [39]. These findings are applicable and helpful to the management of peri-urban areas.

Urbanization in Shanghai metropolitan region dramatically increased the patch density, edge density, shape complexity and diversity for the entire landscape. On the basis of the results of individual land use type, it exhibited distinct and unique patterns that depend on the specific metrics. As the distribution of RL and IL became more scattered, the area of the AL was occupied and experienced more fragmented and irregular patterns in suburbs. The residents and governments, in order to produce more revenue from land sales, expanded RL and IL outward in a disorderly manner. The new growth of urban districts was often generated by the elimination of semi-natural areas in satellite cities or suburbs around the existing urban places [5]. Great loss due to high vulnerability of agricultural land was a direct consequence of high-intensity land use, and has been highlighted in previous studies [33,40]. In addition, the constant decrease of AL was partly due to the abandoned farmland which was widespread in Yangtze River delta [9]. Considering the large variation of PF and GL along the gradient, the inequality in basic public service, ecological and environmental conservation is about the gap between urban and countryside, as well as within satellite towns. In addition, the construction of GL and PF had not kept pace with the rapid urbanization, and formed the uneven distribution of public utilities and green facilities in time and space. The gap between urban and rural areas remain large. In general, according to Weng [24], landscape fragmentation, and irregularity and diversity have a positive relationship with urbanization level in the rapid urbanization stage (T1). However, the authors found no significant relationships among them in T2. This is due to its complex changes of landscape patterns in coalescence process of urban expansion. As a whole, the results of spatial and temporal landscape pattern above were similar to that reported for other large cities around the world, urbanization along the urban–rural gradient showed a complex form in this study.

5.3. Gradient Analysis along Railway Route as a New form Transects

Human activity is a major force in shaping landscape structure with a mix of natural and human-made patches that vary in type, size, shape and arrangement, generating anthropogenic gradients with a specific succession of natural–cultivated–suburban–urban landscapes [33,41]. From an ecological perspective, the urban–rural gradient belts should be able to capture the structure and function of human influence in the temporal and spatial differences from rural to urban landscapes [13]. An alternating process of diffusion and coalescence, and distinctly gradient variation were observed along the gradient analysis, tested that the railway was effective as a gradient element to analyze the landscape pattern changes with urbanization. Different from the unimodal shape patterns in previous studies [8,28], multiple peaks of metrics were exhibited in our experiment. Not just intensive natural landscapes but also the land covers dominated by built-ups were characterized with relatively low variability for these metrics. Whereas the urban–rural transitional landscapes had the highest variability for landscape metrics, due to their intrinsic characteristics of the mixed and complicated components in land use data. Comparing the two sides of the urban center in the transect, metrics exhibited similar patterns, but with more peaks exhibited in the region A than region B. This indicated that the urbanization process was more complex in Songjiang and Minhang district. Thus, it can be seen that different results may be obtained using different transect of the partitions in a study area.

The roadscape transect approach, introduced in this study, is based conceptually on a landscape ecological perspective, and it serves as a more effective measure than former measures to quantify land use structures (five land use types) and processes (spatiotemporal patterns). It illustrated the influence of human activities on natural landscape structure with the sizes, shapes and distributions along the railway that started from downtown, and stretched to the northwest and southwest. Verburg et al. [42] pointed out that accessibility was one of the most important factors of the urban expansion, as well as a key part of classical urbanization theory. As a result, the areas close to the roads have a greater chance of becoming urban expansion zones [43]. Based on the analysis of variability of the landscape metrics using spatial gradient analysis along main roads, scholars assessed the influence of roads on the settlement pattern of the urbanization process [35,43,44]. Compared to the previous studies, the railway approach can overcome the weaknesses of other road approaches due to its advantage in detecting the landscape patterns across urban core area. Furthermore, the gradient approach we performed can comprehensively integrated advantage of both circular buffer zones and moving window method. In addition, the variations of landscape metrics in T2 is smaller than that in T1, demonstrating the railway decreased its disturbances of surrounding landscapes.

5.4. The Suggestion and Implications for Urban Development

Combining gradient analysis with landscape metrics, the spatial and temporal pattern of urbanization were discovered by examining landscape metrics variations that stretch from the urban center, through the suburbs, and to the rural area in Shanghai. According to the study, the area loss of agricultural land with high fragmentation, which was stated to have negative effects on humans and nature [45,46], was already a severe problem in large cities like Shanghai around the world [47,48]. As a result, the rapid reduction of arable land and the prevailing abandoned farmland in this area not only resulted in great waste of land resources, but also decreased the resilience of eco-environment [49]. From the perspective of landscape ecology, the authors suggested to merge fragmented farmland patches into the core farmland and keep a balance between farmland occupation and compensation. More efficient laws or policies for protecting the valuable farmland need to be introduced in large cities desperately. Formulation of reasonably overall land use plans for using land resources scientifically is necessary.

Our results showed that the expansion of desakota regions resulted in high land use diversity, fragmented structure and irregular shape of both the individual and entire landscape from 1994 to 2006. With the urban fringe extending outward, the built-ups were spread out disorderly and rural residential areas stood alone in the agricultural land, reflecting the weakness of earlier urban plans in this area. Drawn from the lessons of Western countries, the size of cities as well as geographical extent of desakota regions must be tightly controlled by a threshold [50]. Growth control policies need to optimize the configuration and utilization of land-use within the desakota region [11]. The Jiading, Minhang and Songjiang district should take their own traditionally superiorities on the close interactions with Jiangsu and Zhejiang province respectively. In addition, many industrial polluters within the central districts were forced to move to these suburban areas since the 1990s, because the environmental policies focused strictly on controlling pollution emissions in urban area [51]. Accordingly, the authors suggested plan-makers form reasonable industrial layouts by balancing economic growth with the environmental protection.

With greater insight into the changes of landscape patterns along an urban–rural gradient, the uneven distribution of public facilities and green land reflects the existing dual urban-rural socioeconomic structure that was a main obstacle for regional development. Urban-rural equalized development is considered an effective way to narrow the societal, social-economic, and environmental gaps between urban and rural areas in China [52]. According to our findings, the most effective way for urbanization is to relocate public infrastructures and man-made green spaces from the downtown to satellite towns. However, environmental and social assessments as well as public communications should be fully taken in to account in urban development. We suggest city planners preserve natural green spaces over creating new ones during urbanization. You [53] pointed out that urbanization in Shanghai involving demographic, social, economic and spatial processes interacted with each other at a low coupling coordination degree. Therefore, the local government should make more efforts to coordinate urban-rural development. Furthermore, in the context of urbanization and eco-environment protection, the establishment of rational urban planning and land use policies for urban and rural integration frameworks are urgent in order to achieve coordinated urbanization development not only for Shanghai city but for the Yangtze River Delta urban agglomeration.

6. Limitations

In this paper, we proposed an explicit methodology paradigm for the detection and characterization of different landscapes expressed by land use gradients, it still has some limitations. Firstly, the integration of landscape ecology with socioeconomic and management practice needs to be strongly emphasized in the future. Secondly, our current studies were only focused on broad land categories. The effect on the final analysis of WD, UL and TR slightly exists. Further studies could extend to include quantitative changes and patterns of other land covers, such as forest, grassland, river and lake, in order to explorer ecological impacts of desakota development in depth. Finally, more GIS-based models for the research in driving forces and prediction of urban expansion should be introduced in our future work.

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