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Sixty-Year Changes in Residential Landscapes in Beijing: A Perspective from Both the Horizontal (2D) and Vertical (3D) Dimensions

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Abstract: Landscape changes associated with urbanization can lead to many serious ecological and environmental problems. Quantifying the vertical structure of the urban landscape and its change is important to understand its social and ecological impacts, but previous studies mainly focus on urban horizontal expansion and its impacts on land cover/land use change. This papers focuses on the residential landscape to investigate how the vertical dimension of the urban landscape (i.e., building height) change through time, and how such change is related to changes in the horizontal dimension of the landscape, using Beijing, the capital of China, as a case study. We quantified the expansion of the residential neighborhoods from 1949 to 2009, and changes in vegetation coverage, building density, and building height within these neighborhoods, using 1 m spatial resolution imagery. One-way ANOVA and correlation analysis were used to examine the relationships of building height to vegetation coverage and building density. We found: (1) The residential areas expanded rapidly and were dominated by outward growth, with much less within-city infilling. The growth rate varied greatly through time, first increasing from 1949–2004 and then decreasing from 2005–2009. The expansion direction of newly built residential neighborhoods shifted from west to north in a clockwise direction. (2) The vertical structure of residential neighborhoods changed with time and varied in space, forming a "low-high" pattern from urban central areas to the urban edges within the 5th ring road of Beijing. (3) The residential neighborhoods built in different time periods had significant differences in vegetation coverage, building density, and building height. The residential neighborhoods built in more recent years tended to have taller buildings, lower building density and lower vegetation coverage.

Keywords: urban expansion; residential landscape; vertical structure; urban landscape; heterogeneity dynamics; building density; building height; urban ecology

1. Introduction

Urbanization and associated changes in landscape structure and function have long been a hot research topic [1–3]. This is because the transforming of natural landscapes into developed land in the process of urbanization can lead to many serious ecological and environmental problems [4,5], such as biodiversity loss [6,7], air pollution [8–10] and urban heat islands [11–13].

Remotely sensed data have frequently been used in studies on landscape changes associated with urban expansion, or urbanization in general [14,15]. A wide range of remotely sensed data have been used in such studies, including AVHRR data with 8 km resolution, medium resolution imagery such as the 250 m/1 km MODIS and 30 m Landsat TM imagery, and high resolution imagery such as the 1 m IKONOS imagery. Most of these studies focus on urban expansion and its impacts on land cover/land use change [15–20]. Recently, there has been an increasing interest in quantifying the fine-scale landscape dynamics within well-developed urban areas [21–23]. These studies all focused on the two-dimensional changes of the landscape. Few studies, however, have investigated changes in the vertical dimension of the landscape, albeit its importance in affecting urban heat islands, air quality and urban residential lifestyle [10,24–26]. This study aims to fill this gap.

In this study, we focused on the residential landscape to investigate how the vertical dimension of the urban landscape (i.e., building height) changes through time, and how such change is related to changes in the horizontal dimension of the landscape (i.e., building density and vegetation coverage). We chose residential landscape because it is where urban residents spend most of their time, and where these changes are perceived [27,28]. In addition, as one of the most important functional zones in the urban landscape, the spatiotemporal pattern of the residential neighborhoods can well reflect the changes of a city.

We chose Beijing, the capital of China, as a case study, and focused on the area within its 5th ring road. We quantified the expansion of the residential neighborhoods within this area from 1949 to 2009, and the changes in vegetation coverage, building density, and building height within these neighborhoods. The overarching goal of this study is to understand the changes in the vertical dimension of the residential landscape, and its relationships to those in the horizontal dimension. Specifically, the objectives of this study are to quantify: (1) the spatiotemporal pattern of the residential neighborhoods in Beijing and (2) the difference in the two-dimensional and vertical dimensional patterns among residential neighborhoods built in different time periods.

2. Materials and Methods

2.1. Study Area

Our study focused on the area within the 5th ring road of Beijing, China (Figure 1). Beijing is the capital of China, located in the northwestern part of the North China Plain (39°28′–41°25′N, 115°25′–117°30′E). It has an area of approximately 16,800 km^2, and a total population of more than 22 million in 2016 [29]. In recent decades, Beijing has experienced a rapid urban expansion, with large areas of natural and agricultural land being converted into built-up areas [20,30].

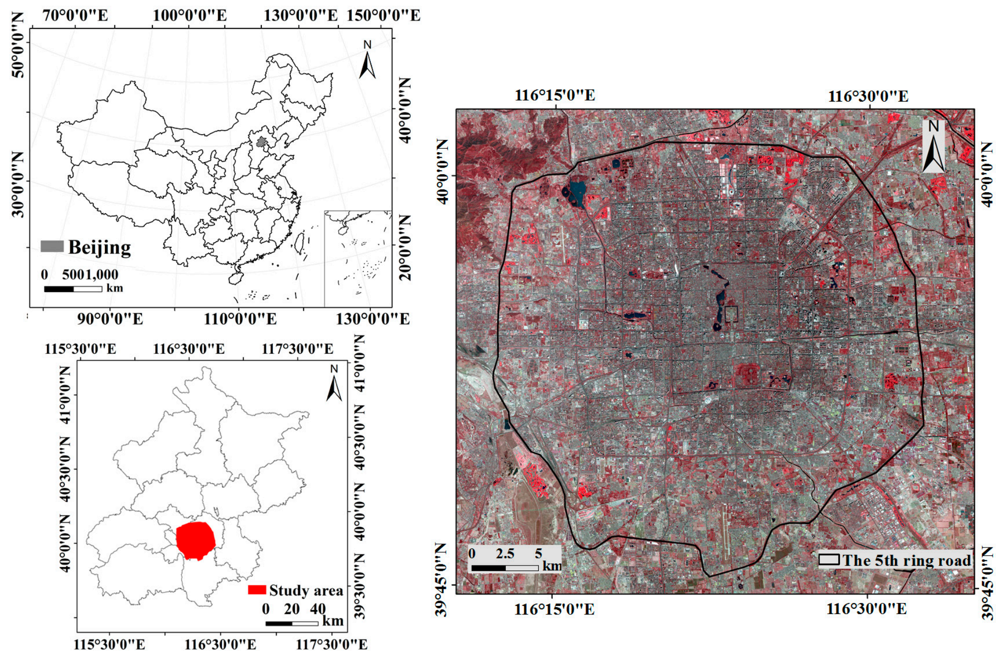

Figure 1. Study Area: the region within the fifth ring road of Beijing, China.

The study area within the 5th ring road of Beijing has a size of approximately 666 km^2 and a total population of 10 million [29]. It is the most developed region in Beijing. The study area is mixed with many different types of land use, and residential land use is one of the dominant uses, accounting for 26.28% of the total area. With the outward expansion and within-city renewal and redevelopment, residential landscape within the study area is spatial heterogeneous and diverse.

2.2. Data

2.2.1. Mapping the Residential Neighborhood

We used the residential neighborhood as the unit analysis. The first step was to map the boundaries of the residential neighborhood in the study area. We did this by visual interpretation based on 1 m spatial resolution GeoEye imagery acquired in 2009, with the aid of zoning maps from Baidu™ map data (map.baidu.com) circa 2010. Information from the website of a real-estate sale company, Lianjia™ (www.lianjia.com) was also used during the process of mapping. In addition, the built years (i.e., housing age) of these neighborhoods were obtained from this website. For the rebuilt neighborhood, the built time is the year in which it was rebuilt. In total, we mapped 2523 residential neighborhoods within the 5th ring road in Beijing (Figure 2). We classified the residential neighborhoods into 5 types based on the built years, which were 1949–1978, 1978–1987, 1988–1997, 1998–2004, and 2005–2009 (Table 1). We did this based on the years when major housing policies were implemented in China.

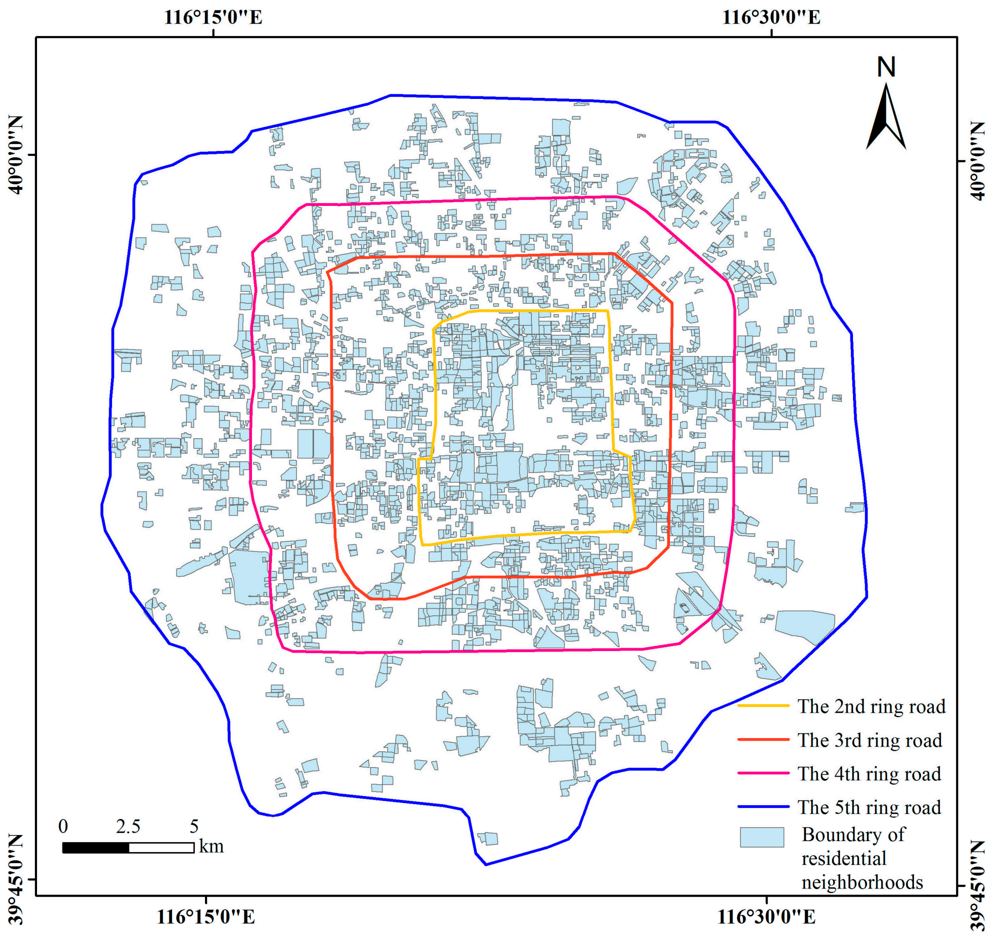

Figure 2. Spatial distribution of the residential neighborhoods within the 5th ring road of Beijing.

Table 1. The five periods when major housing policies were implemented in China.

Periods	Year	Description
1	1949–1978	Before the reform and opening-up policy, with only public owned houses provided for residents.
2	1979–1987	The implementation of the reform and opening-up policy, with the appearance of some private residential buildings.
3	1988–1997	The early years of the housing institution reform and the start of real estate industry; during this time period, the availability of public owned houses decreased.
4	1998–2004	Starting another round of housing institution reform, with dramatic increasing of private residential buildings. The government stopped housing allocation.
5	2005–2009	Period in which the government controlled the real estate market to rein in property prices.

2.2.2. Building Footprint and Height Data

We obtained the data of building footprints and their heights of the residential neighborhoods from Baidu^{TM} map data circa 2010. By referring to the 1 m spatial resolution GeoEye imagery, we found most of the buildings were mapped in the building footprint dataset. The very few missing buildings were digitized by referring to the GeoEye imagery. We calculated the building density for each neighborhood (Table 2).

Table 2. Variables of characteristics of the residential neighborhood.

	Parameters	Unit	Formulas
Features	Built year	year	
	Area of residential neighborhood (S)	m^2	
	Number of annual built neighborhoods	-	
2D Landscape metrics	Building density (BD)	-	$BD = \frac{\sum_{i=1}^{n} Si}{S}$
	Vegetation coverage (VC)	-	$VC = \frac{S_g}{S}$
3D Landscape metric	Mean building height ($\overline{H}$)	m	$\overline{H} = \frac{1}{n}\sum_{i=1}^{n} Hi$

Notes: n is the number of buildings in a residential neighborhood; Hi is the height of the building in a residential neighborhood; S is the total area of a residential neighborhood; Si is the base area of the building in a residential neighborhood and S_g is the greenspace area in a residential neighborhood.

The dataset also included the number of floors for each building. However, such information was missing for a considerable amount of buildings. We used the street view of Baidu^{TM} map to obtain the number of floors for those buildings. We further calculated the building height by multiplying the number of floors by 3 m, which is defined as the typical height of one floor by the Residential Building Code [31].

In addition, we classified the residential neighborhoods into four categories based on the number of floors of the buildings within the neighborhoods (Table 3), following the Chinese building classification in the Code for Design of Civil Buildings [32].

Table 3. Classification of the residential neighborhoods in terms of building height.

Types	Storey	Number (Percentage)	Area (ha) (Percentage)
Low-rise residential neighborhood	1–3	474 (18.8%)	87.86 (40.2%)
Multi-storey residential neighborhood	4–6	1083 (42.9%)	75.95 (34.7%)
Mid-rise residential neighborhood	7–9	423 (16.8%)	23.33 (10.6%)
High-rise residential neighborhood	>9	543 (21.5%)	31.79 (14.5%)

2.2.3. High Resolution Land Cover Data

High spatial resolution land cover data were also used in this study to investigate the land cover and changes within each residential neighborhood. We used Advanced Land Observation Satellite (ALOS) imagery for land cover classification. The ALOS imagery has a panchromatic band with resolution of 2.5 m and four multispectral bands with resolution of 10 m. The imagery was acquired in 22 October 2009. We pan-sharpened the multispectral bands with the panchromatic band, resulting in multispectral bands with a spatial resolution of 2.5 m.

We used an object-based approach for land cover classification. An object-based approach first segments the imagery into objects, on which classification is then conducted [23,33]. An object-based approach provides a more effective and efficient means for high spatial resolution imagery classification, as it can not only use the spectral information, but also texture, context, and spatial relation [23,33]. We identified four land cover classes in this study, including vegetation, impervious surface (including buildings), water and bare soil. The overall accuracy of classification was 94.14%, with a Kappa statistic of 0.92. We calculated the vegetation coverage for each residential neighborhood (Table 2).

2.3. Statistical Analysis

Our statistical analysis focused on how the 2-dimensional metrics (i.e., building density and vegetation coverage) and 3-dimensional metric (i.e., building height) changed through time. We first used Kruskal–Wallis one-way analysis of variance (ANOVA) to test whether the residential neighborhoods built in the 5 different periods had significant differences in proportional vegetation coverage, building density, and building height. We then used Pearson correlation analysis to examine the relationships between the built year of residential neighborhoods and the building density, proportional vegetation coverage, and building height.

3. Results

3.1. The Spatiotemporal Pattern of Residential Landscape in Beijing

3.1.1. Expansion of the Residential Landscape

The expansion of the residential neighborhoods was dominated by outward growth, with much less within-city infilling development (Figures 3 and 4). More than 60% of the residential neighborhoods built before 1978 were located in the urban core areas within the 2nd ring road. The residential neighborhoods built during the time period of 1979–1987 mostly occurred between the 2nd and 3rd ring road, with a percentage of 37.3%. From 1988–1997, newly built residential neighborhoods expanded outwards and were mainly located in areas between the 2nd and 3rd ring road and the 3rd ring and 4th ring road, with percentages of 33.4% and 33.1%, respectively. The residential neighborhoods expanded continuously outwards, with new neighborhoods mostly in the locations between the 4th and 5th ring road during the time period of 1998–2009. The proportion of newly built residential neighborhoods located between the 4th and 5th ring road was 33.8% in 1998–2004, and 44.1% in 2005–2009. While the development of the residential neighborhoods mainly tended to expand outwards, within-city infilling development increased through time, particularly in recent years. For example, more than 40% of the residential neighborhoods located in the area between the 2nd and 3rd ring road were built during 1998–2009 (Figures 3 and 4a).

Although the region between the 3rd and 5th ring road had more residential neighborhoods, the region within the 3rd ring road had a higher neighborhood density (Figures 3 and 4b). The region within the 2nd ring road had the highest density in all 5 periods, and the area between the 4th and 5th ring road always had a consistently lower neighborhood density than other regions. Neighborhood density in Beijing had a rapid growth during the period of 1998–2004 and then slowed during 2005–2009.

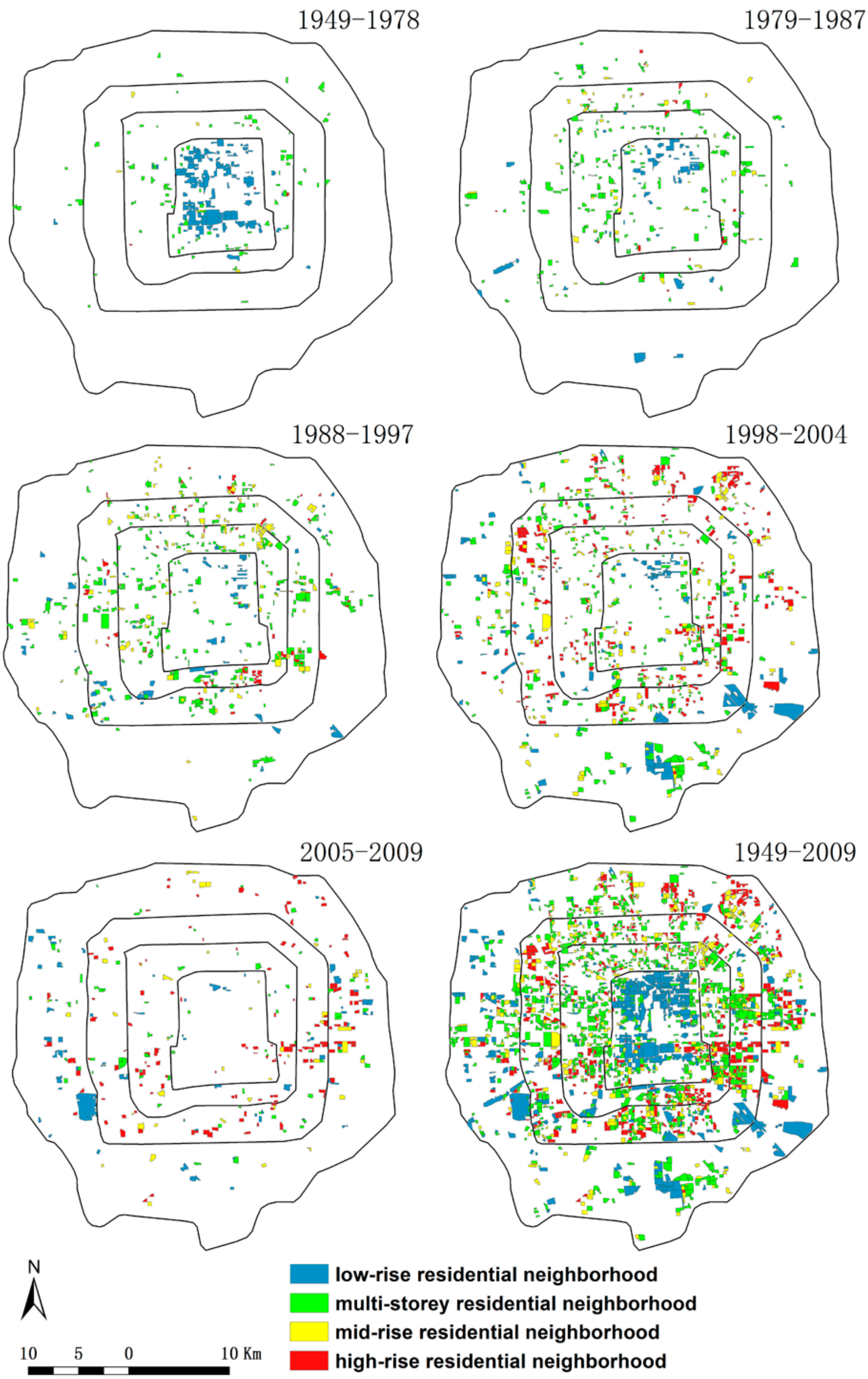

Figure 3. Spatial distribution of the residential neighborhoods within the 5th ring road of Beijing in different time periods.

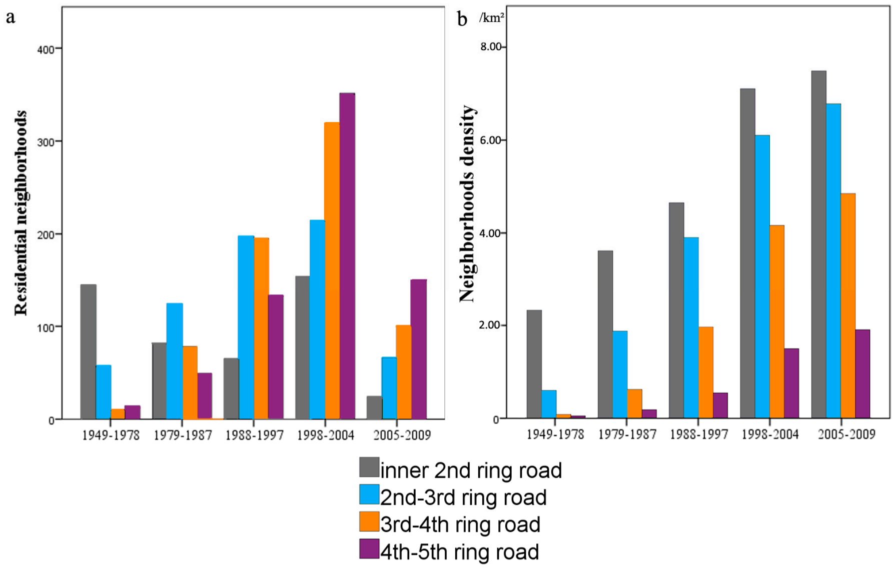

Figure 4. Quantity changes of the residential neighborhoods in regions within the 5th ring road of Beijing in different time periods: (**a**) Number of newly built residential neighborhoods; (**b**) Variation of neighborhood density, where neighborhood density is the number of residential neighborhoods per km^2.

The spatial distribution of the residential neighborhoods is heterogeneous and varied by time. The majority of the residential neighborhoods is located in the northern and eastern region of Beijing, with much less in the southern part (Figure 5). The residential neighborhoods built before 1979 are mainly located in the urban center area (64.2%). Approximately 41% of the residential neighborhoods built during 1979–1987 are located in the western and northwestern part of Beijing. The residential neighborhoods expanded towards the northern (21.9%) and northeastern (15.0%) part during 1988–1997. During 1998–2004, the residential neighborhoods expanded notably in all directions. An increased number of residential neighborhoods was built in the southern part (13.6%), but still less than that in the northern (17.7%) and northeastern (14.0%) regions of Beijing. Most of the residential neighborhoods built during 2005–2009 are located in the eastern region of Beijing (24.2%). Overall, the development of the residential neighborhoods in Beijing shifted from west to north in a clockwise direction (Figure 5). This dramatic increase in the residential neighborhoods in all directions might be related to the housing policies in this time period, during which another round of housing institution reform was implemented (Table 1).

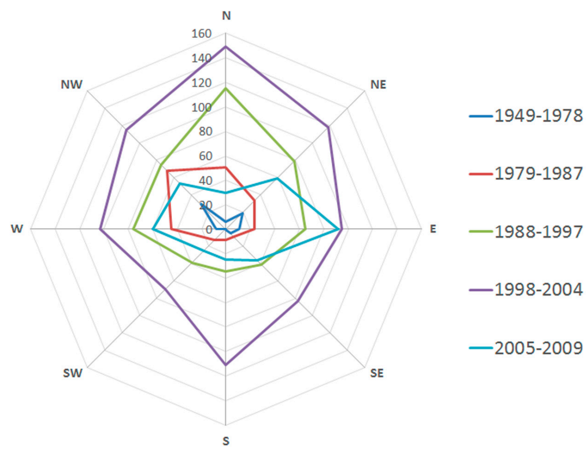

Figure 5. Distribution of the residential neighborhoods within the 5th ring road of Beijing in different directions.

The growth rate varied greatly through time, with a continuous increase from 1949–2004 and then a decrease from 2005–2009 (Table 4). The total area of the residential neighborhoods that developed during the time period of 1949–1978 was 18.09 km^2, with the lowest annual growth rate (0.6 km^2/year). However, the mean size of the residential neighborhoods built during this time period was the largest (8 ha). The residential neighborhoods started to expand rapidly from 1979. The total area of the residential neighborhoods increased by 19.81 km^2 in 1979–1987, 35.42 km^2 in 1988–1997, and 66.82 km^2 in 1998–2004, with an annual growth rate of 2.2 km^2, 3.54 km^2, and 9.55 km^2, respectively. The size of the residential neighborhoods became smaller (6 ha) and was similar in these three time periods. The growth rate slowed to 5.02 km^2/year from 2005–2009, resulting in a total area of 25.11 km^2 in newly developed residential areas.

Table 4. Expansion of the residential neighborhoods in different time periods.

Classification	Built Year	Total Area of Newly Built Residential Neighborhoods (km^2)	Annual Increasing Rate of Residential Neighborhoods (km^2/year)	Mean Area of Residential Neighborhoods (ha)
1	1949–1978	18.09	0.6	8.0
2	1979–1987	19.81	2.2	6.0
3	1988–1997	35.42	3.54	6.0
4	1998–2004	66.82	9.55	6.4
5	2005–2009	25.11	5.02	7.4

3.1.2. Vertical Structure of the Residential Landscape

The vertical structure of the residential neighborhoods changed greatly through time from 1949–2009 (Figures 3 and 6). Most of the residential neighborhoods built before 1979 were low-rise residential neighborhoods with buildings of no more than 3 floors. There were few residential neighborhoods having buildings with more than 6 floors. The percentage of mid-rise and high-rise residential neighborhoods was only 4.5% during that time period. The residential neighborhoods built from 1979–2004 were dominated by buildings with 4–6 floors, particularly in the early years. For example, 64.8% of the buildings had 4–6 floors. Meanwhile, the proportion of high-rise buildings continued to increase, from only 5.7% in 1979–1988 to 11.2% in 1989–1997, and 29.2% in 1998–2004. During 2005–2009, high-rise apartments became the dominant building type in the residential neighborhoods, accounting for 44.4%. As discussed above, the residential neighborhoods mostly expanded outwards. Consequently, the vertical structure of the residential landscape was gradually built into a “low in the center, high at the edge” form. That is, the low-rise residential neighborhoods with a relatively long history within the 2nd ring road were surrounded by medium- and high-rise residential neighborhoods distributed between the 3rd and 5th ring road in Beijing (Figure 3).

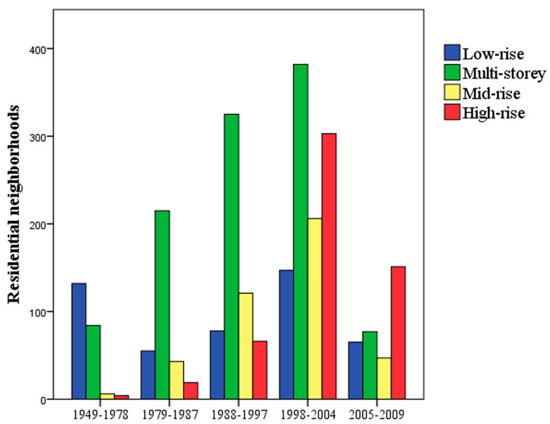

Figure 6. Number of different residential neighborhood types within the 5th ring road of Beijing in different time periods.

3.2. Changes within Residential Neighborhoods through Time

We found the residential neighborhoods built in different time periods had significant differences in vegetation coverage, building density, and building height (Figure 7). The highest proportional vegetation coverage occurred in the residential neighborhoods built in 1979–1978 (0.28), while the lowest coverage occurred in 2005–2009 (0.20). The residential neighborhoods built in 1949–1978 had the highest building density (0.33) and the lowest average building height (9.07 m), whereas those built in 2004–2009 had the lowest building density (0.2) but the greatest height (25.93 m).

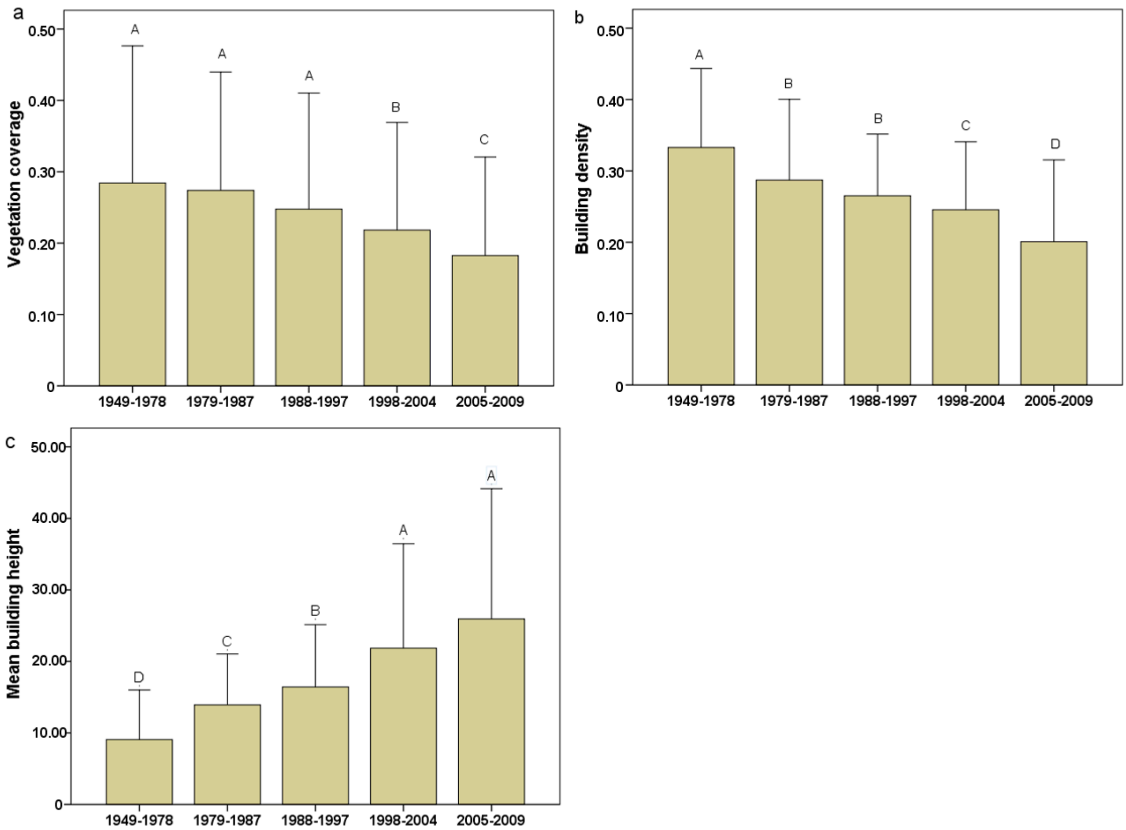

Figure 7. Results of one-way ANOVA on (**a**) vegetation coverage, (**b**) building density and (**c**) building height among different time periods. Superscripted letters indicate a significant difference among different time periods ($p < 0.05$). Different letters indicate significant differences, and the same letters indicate no significant difference.

The Pearson correlation analysis results showed that vegetation coverage, building density and building height were all significantly correlated with the built year of residential neighborhoods (Table 5). Building height had a significantly positive relationship with built year, while building density and vegetation coverage had significantly negative relationships (Table 5). Further correlation analyses were conducted to investigate the relationship between vegetation coverage, building density and building height (Tables 5 and 6). The results showed that there was a significantly negative correlation between building density and vegetation coverage, while building height had a significantly negative relationship with both of these variables from 1949–2009. In the five time periods, the vegetation coverage was negatively correlated with building density, and building height had a significantly negative relationship with building density, but building height had no significant correlation with vegetation coverage in all five time periods.

Table 5. Pearson correlation coefficients between built year of residential neighborhood and building height, building density, and vegetation coverage.

	Built Year	$\overline{H}$	**BD**	**VC**
Built year	1	0.347 **	−0.322 **	−0.158 **
$\overline{H}$		1	−0.317 **	−0.095 **
BD			1	−0.135 **
VC				1

** Coefficient is significant at the 0.01 level.

Table 6. Pearson correlation coefficients between building height, building density and vegetation coverage in the five time periods.

		$\overline{H}$	**BD**	**VC**
1949–1978	$\overline{H}$	1	−0.377 **	0.009
	BD		1	−0.237 **
	VC			1
1979–1987	$\overline{H}$	1	−0.387 **	−0.072
	BD		1	−0.132 *
	VC			1
1988–1997	$\overline{H}$	1	−0.288 **	0.072
	BD		1	−0.231 **
	VC			1
1998–2004	$\overline{H}$	1	−0.237 **	−0.05
	BD		1	−0.245 **
	VC			1
2005–2009	$\overline{H}$	1	−0.159 **	−0.088
	BD		1	−0.139 *
	VC			1

* Coefficient is significant at the 0.05 level. ** Coefficient is significant at the 0.01 level.

4. Discussion

Our results on the changes in the building height of the residential landscapes underscore the importance of considering the vertical dimension in spatial pattern analysis. The commonly used two-dimensional analysis may miss important changes in the residential landscapes. For example, there was no significant difference in building density and vegetation coverage between the residential neighborhoods built in the two time periods of 1979–1987 and 1988–1997 (Figure 7a,b). However, the average building height of residential neighborhoods greatly increased from 13.9 m in 1979–1987 to 16.4 m in 1988–1997 (Figure 7c). Previous studies have also demonstrated that the inclusion of the vertical dimension can provide better understanding of changes in landscapes (e.g., [34,35]).

Our results showed that building height varied greatly in the residential neighborhoods built in different years. The residential neighborhoods built in more recent years tended to have more tall buildings and thus greater average building height. These high-rise residential apartments were built to meet the need of accelerated population growth in Beijing and to improve the land use efficiency [36,37]. The changes in the height of the residential neighborhoods and their spatial distribution may have great social-ecological implications. On the one hand, extending "urban growth" to the vertical dimension, that is, building high-rise apartments, can greatly improve the land use efficiency, and therefore reduce the adverse impacts of urban expansion on replacing natural landscapes or agricultural lands. The increase in open space and greenspace in a residential neighborhood can also provide a variety of social and ecological benefits to its residents [38–41]. In addition, the living environment of residential neighborhoods can benefit from building high-rise apartments in some aspects [42]. For example, the residential neighborhoods with greater average building height tend to have lower land surface temperature [43–45]. This is likely because the residential neighborhoods with higher buildings tend to have lower building density, and higher proportional greenspace coverage (Tables 5 and 6). Additionally, high-rise buildings can provide large shaded areas that also can effectively reduce the surface and air temperature [44,46,47].

On the other hand, the spatial distribution of the residential neighborhoods with different building height may have some adverse social and ecological impacts. In Beijing, the downtown area is mostly dominated by the residential neighborhoods with relative low buildings, which is surrounded by high-rise apartments located from the 3rd ring road to the 5th ring road. This forms a "low-high" pattern from the central area to the edge (Figure 3). Taking the thermal environment as an example again, these clusters of neighborhoods with high-rise buildings in the outer-rings may block urban ventilation [48,49] and therefore aggravate the urban heat island effects, as well as prevent the diffusion of air pollutants in the urban central areas [24,50,51]. The social and ecological impacts of the vertical structure warrant further research.

Recent advances in Light Detecting and Ranging (LiDAR) and unmanned aerial vehicle technology greatly increase the availability of vertical dimensional data in an affordable way [52–55]. These advances will greatly facilitate the quantitative analysis of the vertical structure of the urban landscapes and their social and ecological impacts. Such analysis would be highly desirable, not only for urban ecologists to better understand the structure of the urban landscape, but also for urban planners and designers to better manage the urban landscape.

5. Conclusions

Quantifying the vertical structure of the urban landscape and its change is important to understand its social and ecological impacts. Our study focuses on the residential landscape to investigate how the vertical dimension of the urban landscape (i.e., building height) changes through time and how such change is related to changes in the horizontal dimension of the landscape. We found that (1) in different time periods, the spatial distribution of newly built residential neighborhoods is different. Overall, the expansion mode of the residential neighborhoods within the 5th ring road in Beijing during 1949–2009 was dominated by outward growth, with much less within-city infilling. The growth rate varied greatly through time, first increasing from 1949–2004 and then decreasing from 2005–2009. The neighborhood density is higher in center area and lower in urban edges. The expansion direction of newly built residential neighborhoods shifted from west to north in a clockwise direction. (2) The residential neighborhoods also developed in the vertical space, which formed a "low-high" pattern from the urban central area to the urban edges within the 5th ring road in Beijing. (3) The landscape pattern of the residential neighborhoods in different time periods is significantly different. The residential neighborhoods built in more recent years tend to have taller buildings, lower building density and lower vegetation coverage than other periods. There was a significantly negative correlation between building density and vegetation coverage, while building height had a significantly negative relationship with both of these variables from 1949–2009.

Our study reveals the distribution of the residential neighborhoods and the change of the residential landscape within the 5th ring road in Beijing during 1949–2009. The study aims to strengthen the understanding of residential area change and to provide a methodological basis for urban planning and policy making. This paper did not involve the study of the driving force underlying the change in residential neighborhood landscape patterns, which has great significance for urban planning. It could be studied in further research.

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

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