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A Novel Model for Detecting Urban Fringe and Its Expanding Patterns: An Application in Harbin City, China

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Abstract: Urban fringe is an active expanding belt, indicating urban-rural interaction processes. Previous studies have attempted to define urban fringe as the transitional area between urban and rural areas, but there is a lack of quantitative analysis of the periphery boundaries. We developed a novel, the Spatial Segmentation Model (SSM), to detect the extent of urban fringe via calculating the share of the built-up land. Within the urban fringe, we statistically compared the number of built-up patches in each direction and described four urban expanding patterns (stable, sprawling, leaping, and mixing patterns) indicated by the empirical analysis. The results show that this model can reliably detect the urban fringe and could reveal urban growth characteristics. We find the spatial territory changes are highly relative with transport infrastructures in Harbin. Meanwhile, the roads density in the urban core are higher than in the urban fringe. Especially for city roads, roads density in the urban core is more than 4 times higher than in the urban fringe. The growth of the urban fringe is closely related to the development of social economies as well as the space policies and development plans designed by governments. Similar to the post-industry cities worldwide, Harbin should take action to address population decline. Effective land-use and suitable urban growth strategies play an important role in alleviating urban shrinkage. Thus, understanding the dynamics, urban expanding patterns, and driving factors in the urban fringe can help us form a basis for future urban development.

Keywords: urban fringe; landscape fragmentation; urban expansion; Harbin City

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1. Introduction

Urban fringe is an active expanding belt, lying between urban landscapes and agricultural hinterlands [1–3]. In most cities and regions, urban expansion has resulted in the loss, displacement, and fragmentation of agricultural land and natural habitats [4–6]. If this trend continues, urban expansion will lead to irreversible and unsustainable land-use transitions [7,8]. The impacts of urban expansion first appeared in urban fringe [9]. Urban expansion may result to landscape fragmentation in the urban peripheral areas [1,10], presenting as increasing the number of built-up land patches and/or dividing agricultural land or natural habitats into smaller independent patches [11–13]. This process results in spatially heterogeneous and complex land-use configurations [14–17]. Thus, the urban fringe is characterized by highly dynamic and spatially heterogeneous areas [18–20]. This process takes place in fringe areas, because it's relatively low land prices with limited transport, shopping, and entertainment infrastructure [21,22] compared to that in central urban areas [20].

The identification of the urban fringe mainly involves two perspectives, of which location is considered in absolute spatial positions based on land-use characteristics in the grid, and/or in relative spatial positions. Although the definition of urban fringe mainly describes its relative location in the urban-rural spatial territory, rather than its absolute location [3]. Most studies have adopted landscape classification methods, combined land-use, land use intensity, as well as other natural and human factors, from an absolute spatial perspective. For example, Wang et al. [23] think urban fringe is a part of the urban system, which can be distinguished as peri-urban areas and suburban areas based on the share of built-up land and population density in each grid. Most similar studies mainly consider urban fringe as an interface area with specific characteristics, i.e., built-up land sprawling and subsequent agricultural land conversions [24–26]. Different from urban landscape classifications, detecting urban fringe (regarded as a gradient zone from urban landscapes to agricultural hinterlands) aims to explore special urban zones and then carry out special urban management and planning strategies. Yet, few quantitative studies have focused on detecting special urban zones, even in urban fringe, on urban-rural spatial territories.

Fortunately, the use of an urban-to-rural gradient view beyond the urban-rural dichotomy is a positive development in detecting urban fringes [15,27–29]. The continuous spatial arrangement of land-use gradients can be utilized to understand landscape structures and potential land-use variations between urban and rural areas [20]. The application has some advantages, such as minimizing subjectivity in variability measurements concerning the spatial attributes of land-use patches and improving our ability to describe landscapes characteristics [30–32]. Thus, a number of quantitative models have been developed to detect urban fringes based on gradient variations of spatial attributes between urban and rural areas in terms of socio-economic, land-use, population density, and natural-terrain factors [33–37]. Among these models, mutation detection of the gradient variations in built-up land patches for housing populations and their activities are most commonly used to characterize the divide between urban and rural areas [1,4]. Among them, Peng et al. [38] proposed a new model, combining wavelet transform and kernel density estimation, to delineate the boundary of the urban fringe based on land use data. An improved model of message entropy for land-use, and/or the degree of landscape disorder extracted from remote-sensing imagery, have also consistently been attempted [39,40]. However, it is difficult to overcome the subjectivity inherent in defining and determining cut-off points in regions with scattered land-use composition [1,38].

In the urban fringe, we can explore urban expanding patterns based on its internal changes to manage them with different strategies. There are numerous empirical studies on urban expanding patterns in the peripheral areas of big cities [36,41,42]. Feng et al. [43] has measured the urban expanding process using integrated indicators in the urban fringe of Jiangning (a district in Nanjing, China), which is sprawling rapidly. More comprehensively, Sui and Lu [44] indicates the characteristics of the urban fringe in China, which varies due to the suburbanization of foreign cities. To further explore urban expanding patterns, studies commonly analyze the characteristics of urban expansion through calculation of geometric parameters pertaining to built-up land; these geometric parameters include fractal dimensions of the urban contour, compactness, shape indexes, gravity center coordinates, extended intensity, extended gradient, and the extended elasticity coefficient, among other factors [45–47]. In addition, some use the convex hull method to determine urban expanding patterns quantitatively [48,49]. Unfortunately, the convex hull method only considers contiguously developed urban areas and adjacent regions, thereby disregarding the impacts of urban expansion in the gradually-transforming regions between urban and rural areas.

This study constructs a novel approach to detect the urban fringe in Harbin City. The main aims of this paper are: (1) to quantitatively delineate the boundary of the urban fringe via parameterized built-up vector data, (2) to quantitatively determine urban expanding patterns in the urban fringe zone according to the boundary of the urban fringe and the number of built-up patches, and (3) to analyze the possible driving forces behind changes in urban expanding patterns. The rest of this paper is organized as follows: in the Materials and Methods section, we introduce the study area, data sources, and study methods including the Spatial Segmentation Model (SSM), the maximum fragmentation boundary (MFB), and urban expanding pattern deduction; in the Results section, we parameterize the SSM to obtain the urban fringe boundary and identify the MFB to determine urban expanding patterns in the urban fringe. Then we analyze the changes in urban fringe and explore the changes and forces driving urban expansion. In the discussion section, we discuss this new method and its potential for application. Finally, we examine the interaction between urban fringe development, socio-economic growth, and other factors that affect urban fringe development in Harbin.

2. Materials and Methods

2.1. Study Area

Harbin City is an important hub within the Eurasian Land Bridge and the capital of Heilongjiang Province, lying in the eastern region of the Songnen Plain (see Figure 1). Nevertheless, its economy is underdeveloped when compared with other Chinese cities, with a built-up land growth rate of less than half the national average between 1984 and 2019 (China City Statistical Yearbook, https://navi.cnki.net/knavi/yearbooks/YZGCA/detail?uniplatform=NZKPT/, accessed date 19 August 2021). The non-agricultural population of municipal districts in Harbin reached 5.51 million in 2019; thus, it is classified as a big city in China, but research focusing on its urban growth is scarce. Our study area includes six districts comprising the urban area of Harbin City: Nangang District, Daoli District, Daowai District, Xiangfang District, Songbei District, and Pingfang District, for which the coordinates are 126°8′36″–126°59′38″ E, 45°31′35″–46°5′38″ N and the total area is 2451.73 km^2. This work therefore provides an empirical case study on the spatial structure of an underdeveloped northern metropolis.

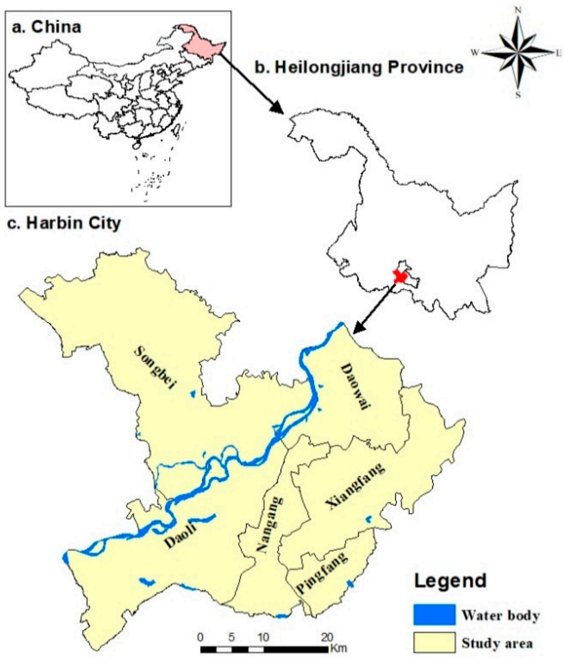

Figure 1. Study area. Harbin lies in the southern region of Heilongjiang province, which is located in Northeastern China.

The end of a nine-year period of continuous net loss of industrial production in 2000 was an important turning point for this rust belt city [50]. Its economic upswing was driven by a number of factors: First, the 10th, 11th, and 12th Five-Year Plans for Harbin better arranged the layout of its urban resources, including land use, industrial space, and transport infrastructure construction [51,52]. Then, the 2002 Harbin Development Strategy Plan put forward a five-part development strategy that included a focus on science and education, industrial restructuring, urban functions reengineering, urban spatial structure, and flow space upgrading. Furthermore, China's national government proposed a transformation and revitalization strategy for older industrial regions, including the Northeast Revitalization Plan, which is not only actively promoted investment in infrastructure, but also attracted a large amount of foreign investment [53]. However, the Northeast Revitalization Plan heavily relies on investment-driven programs [54]. Meanwhile, a large amount of capital was invested in heavy industries and resources-oriented industries, rather than services sectors and the information and technology industry [54]. These experiences show major challenges in Harbin for its revitalization and urbanization process.

2.2. Data Source

We obtained remote sensing images from the Landsat 4-5 TM and Landsat 8 OLI/TIRS sensors for the years 1991, 2000, 2010, and 2015 from the United States Geological Survey (https://earthexplorer.usgs.gov/, accessed date 1 September 2018). To distinguish built-up land with the aid of spectrum characteristics, we selected images with vegetation, and without snow and clouds between June and September. Detail image information can be found in Table 1, including the entity ID, acquisition date, data set, and spatial resolution.

Table 1. Image data information.

Year	Entity ID	Acquisition Date	Data Set	Spatial Resolution
1991	LT51180281991165HAJ00	1991-06-14	Landsat 4-5 TM	30 m
2000	LT51180282000158HAJ03	2000-06-06	Landsat 4-5 TM	30 m
2010	LT51180282010265MGR01	2010-09-22	Landsat 4-5 TM	30 m
2015	LC81180282015167LGN00	2015-06-16	Landsat 8 OLI/TIRS	15 m

We used ENVI 5.3 (http://www.esrichina.com.cn/, accessed date 1 September 2018) to preprocess each image, which involved geometric correction, layer stacking, image color enhancement processing, and clipping. We synthesized simulated true color (band 7, 4, 3) and standard false color (band 4, 3, 2) images for Landsat 4-5 TM. For Landsat 8 OLI/TIRS, we used the band 8 (full color channel) to sharpen images with the Gram-Schmidt Pan Sharpening tool, thereby forming a standard false color (band 5, 4, 3) image with a 15 m resolution. After these procedures, the built-up vector data was obtained by supervised classification and visual interpretation. We compared images in different seasons and/or years to reduce the impact of similar materials with different spectrums, or similar spectrums corresponding to different materials, on image interpretation. In this study, we assumed that built-up land expansion was irreversible during urban development [55]. Parks and green spaces were classified as built-up land because they contribute to ecological and entertainment functions within a city; this classification is also consistent with the definition of built-up land in the "Code for classification of urban land use and planning standards of land development" established by the Ministry of Housing and Urban-Rural Development of the People's Republic of China. We randomly selected 150 sampling points of the built-up land in Google Earth that changed from non-built-up to built-up in 2015. Comparing these sampling points with the interpreted data, we found that the accuracy of the built-up vector data was 96% (Figure 2).

2.3. Methods

Data analysis involved three main steps (see Figure 3): (a) the Spatial Segmentation Model (SSM) was generated to convert the built-up land data into comparably discrete values, then we obtained the inner and outer boundaries of the urban fringe according to the chosen threshold values; (b) the maximum fragmentation boundary (MFB) was calculated using buffer analysis and regression analysis; and (c) urban expanding patterns were used to analyze urban growth evolution processes using the calculated the numbers of built-up patches in each 10-degree section within the urban fringe, the MFB, and the outer boundary of the urban fringe. These steps are detailed below.

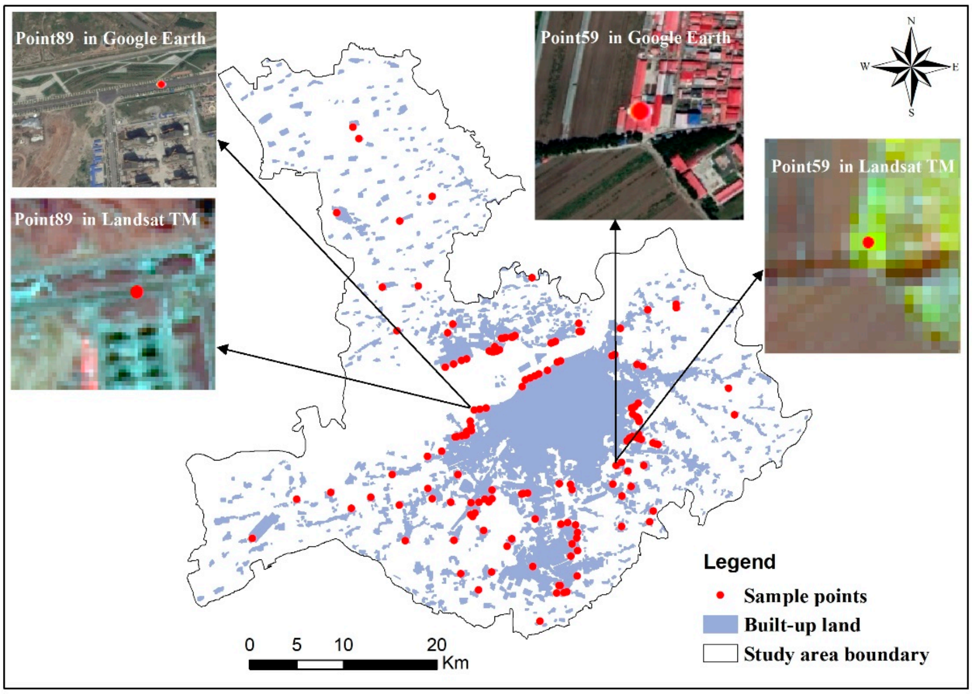

Figure 2. Sample points and result of the interpretation of built-up land in 2015. We selected point 89 and point 59 which were correctly and incorrectly interpreted, respectively, and compared them in Google Earth (Date: 16 September 2015) and Landsat TM (Band 5, 4, 3).

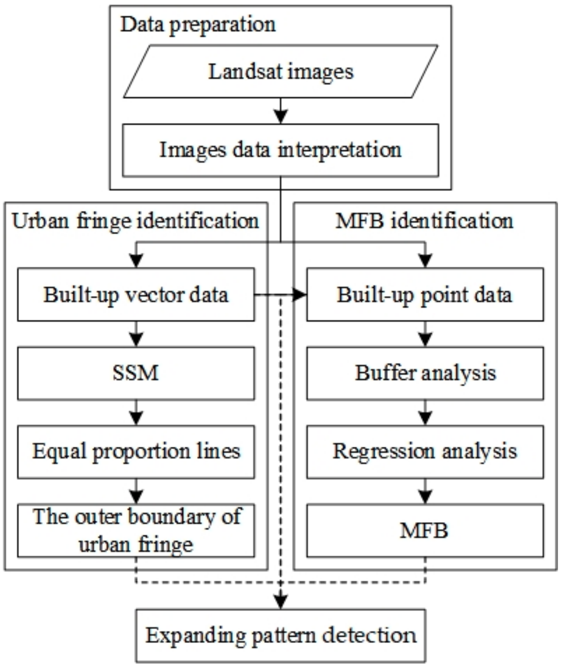

Figure 3. Overview of methods used.

2.3.1. The SSM Development Process

The SSM was built via the procedures detailed below using Python 2.7 (https://www.python.org/, accessed date 1 September 2018) in ArcGIS 10.3 (http://www.esrichina.com.cn/, accessed date 1 September 2018). First, we divided the study area into 360 regular sections around the center point of the largest built-up area. Second, using the "from-short-to-length" concept, we drew a series of stitching line segments of length L in each direction. Longer line segments resulted in shorter computational times and poorer accuracy, while shorter line segments obviously led to greater computational demands but greater accuracy and precision; we eventually selected an optimal line segment length of 50 m. Third, we established a comparable standard, assigning a value to each line segment. The i-th value in each direction is the intersection length (x_i) between the corresponding line segment and the built-up land vector data and is computed via $R_i = x_i/L \times 100\%$ (where $0 \leq R_i \leq 100\%$). The i-th mean value was used to represent the share of built-up area in the corresponding direction and is computed via $M_i = \sum R_i/i$.

Evaluating points in each direction from the urban center, the inner boundary of the urban fringe was defined where M_i was no less than 99.9%, while the outer boundary was defined where M_i was no less than 50%. We obtained the outer boundary threshold by comparing model results using different thresholds to actual traffic facilities and distributions of built-up land.

However, these boundaries could not be used directly for delimiting the urban fringe because of their irregular radial shape. Thus, we corrected the mean value in each direction using a moving average with the formula as follows:

$$P_j = \left(M_{j-3} + M_{j-2} + M_{j-1} + M_j + M_{j+1} + M_{j+2} + M_{j+3}\right)/7 \quad (1)$$

where P_j is the post-corrected value in the j direction and M_j is the pre-corrected value in the j direction.

2.3.2. Maximum Fragmentation Boundary (MFB) Identification

The MFB is defined as the boundary of the area of maximum built-up land fragmentation and represents the outer boundary of the urban fringe in the ideal state. It is based on assumptions that the plain is homogeneous, without the influence of physical elements, and that the built-up land fragmentation is closely related to the distance from the urban core. Based on these three assumptions, we divided the peripheries of the urban core into three ring bands corresponding to distance from the center point as follows: (i) built-up land fragmentation is sensitive to and increases with distance from the urban core, consistent with Weber's and Christaller's location theories [56,57]; (ii) with further distance from the urban core, the effects on built-up land fragmentation decrease as described by "distance attenuation theory" [58,59]; and (iii) the effects of a given urban center decrease as distance increases until the effects from neighboring cities begin to increase.

We calculated the distance from the center point, given by the radius equivalent, using the multiple ring buffer tool in ArcGIS 10.3 (ESRI, http://www.esrichina.com.cn/, accessed date 1 September 2018). Then, the number of built-up patches in each buffer ring was analyzed with a trinomial regression function to yield the MFB. The number of built-up patches is widely used as a simple but effective method to characterize the fragment of the spatial territory [23]. The regression analysis included two steps: (1) counting the number of built-up patches between each buffer ring, and (2) finding the MFB based on statistical data, which involved plotting a scatter diagram and applying a trinomial fit to the data, where the trinomial maximum gives the MFB. We varied the buffer interval as 0.5 km, 1 km, 1.5 km, and 2 km in different years, comparing the goodness of fit (R^2) for each trinomial, then chose a trinomial fit for which the goodness of fit was closest to 1; the calculated maximum for this best-fit trinomial represents the MFB.

2.3.3. Detecting Urban Expanding Patterns

Urban expanding patterns were used to explore forms and the extent of urban spatial growth in each direction, and were calculated using the outer boundary of the urban fringe, the MFB, and numbers of built-up patches. The calculations proceeded as follows. First, the outer boundary of the urban fringe and the MFB were distributed in 360 degrees. The difference between the outer boundary of the urban fringe and the MFB indicates the dynamism of the urban expansion. Positive values indicate urban active expansion, while negative values indicate relatively slower urban expansion. Then, the number of built-up patches was calculated in each 10-degree section in the urban fringe. These values were greater than or equal to zero, where larger numbers indicated greater degrees of built-up land fragmentation [60–62].

According to the results, urban expanding patterns fell into four types: stable, leaping, sprawling, and mixed. These four patterns are defined below (see Figure 4). The stable pattern refers to relatively slow urban expansion in which the degree of built-up land fragmentation is smaller, the difference of the boundary distance is negative, and the number of built-up patches is lower. The leaping pattern involves active urban expansion in which the degree of built-up land fragmentation is higher, the difference of the boundary distance is positive, and the built-up land proportion is larger. The sprawling pattern refers to active urban expansion with a degree of built-up fragmentation less than that of the leaping pattern, with positive boundary differences, and a number of built-up patches that is less than or equal to that of the leaping pattern. Lastly, the mixed pattern refers to the coexistence of leaping and sprawling patterns in areas where it is difficult to distinguish between the two.

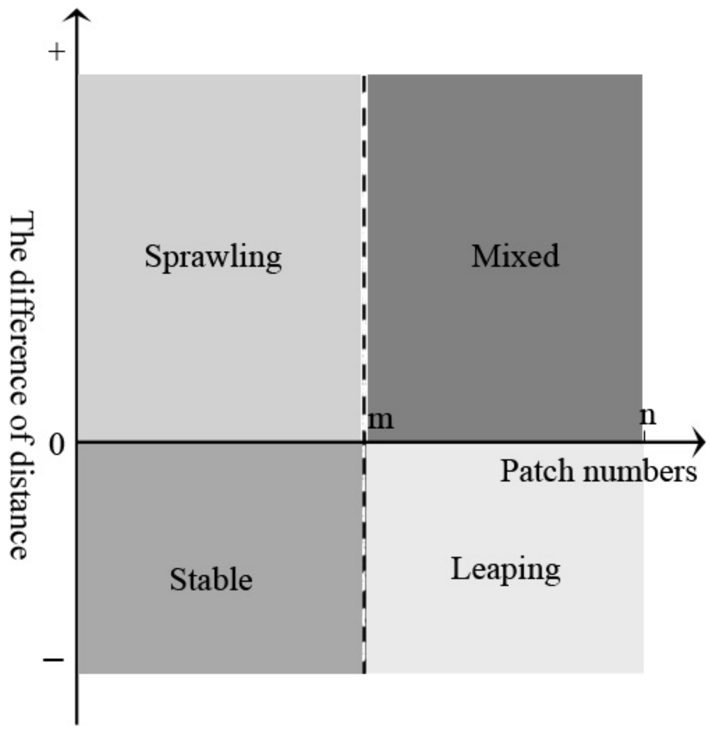

Figure 4. The framework of urban expanding patterns. The horizontal axis shows the number of patches and the vertical axis shows the distance difference between the outer boundary of the urban fringe and the MFB. In the horizontal axis, n is the maximal number of patches in each direction and m is the mean number of the built-up patches in the 36 directions. The scale of the horizontal axis is arbitrary.

3. Results

3.1. Changes of the Urban Fringe in Harbin

The urban spatial territory has changed significantly in Harbin, which was highly relative to transport infrastructures. Figure 5 shows the urban core and the urban fringe in 1991, 2000, 2010, and 2015. The urban core was relatively stable during this period. In 1991, the urban core was largely within the second ring road, which was somewhat delineated by the road and had a "heart" shape. The urban core expanded to the second ring road in 2000, which is roughly bordered by Qianjin Road, Hegu Street, Youyi Road, Daxin Street, Northeast Street, South Road, Gongbin Road, Three Power Road, and Hexing Road. From 2000 to 2015, the urban core expanded irregularly and anastomosed with the third ring road, which was driven by traffic hubs such as the Harbin West Railway Station, Long-Distance Bus Terminal, and Harbin East Railway Station. The changes of the urban fringe were more significant in different directions. The urban fringe was stable and distributed on both sides of the Harbin Ring Expressway (the fourth ring road) in both 1991 and 2000. Between 2010 and 2015, the outer boundary expanded out to the Harbin Ring Expressway and sections surpassed the administrative boundary and spread over the northern border of Songbei District, constituting a significant change in the outer boundary. These changes reflected the growing effects of the Harbin urban core.

The road density's significant variations, due to the differences in population density, developing positioning, and spatial functions in different zones, are shown in Table 2. Due to its intensive building footprint, the roads density in the urban core are higher than in the urban fringe. The expressway distributes outside the urban core and 0.0 km/km^2 in the urban core, which mainly provides transportation services between urban and rural areas as well as between different cities. For both the urban core and urban fringe, the roads density slightly decreased during 1991–2015. Comparing values in the city roads showed that the road density of the first-class city road in the urban core was 4.2 to 7.7 times greater than in the urban fringe. The ratio for the second-class city road was between 4.1 and 5.5. Due to increased transportation investment, roads in the urban core were more dense than in the urban fringe, covering almost a third of the total area of the urban core [19,63]. The road density of the second-class city road was twice that of the first-class city road, which suggests that people need more short-distance roads.

Table 2. Roads density in different zones in 1991, 2000, 2010, and 2015.

	Urban Core				**Urban Fringe**			
	1991	**2000**	**2010**	**2015**	**1991**	**2000**	**2010**	**2015**
Railway	0.18	0.17	0.16	0.15	0.09	0.08	0.07	0.06
Expressway	0.00	0.00	0.00	0.00	0.71	0.77	0.64	0.66
State Road	0.59	0.44	0.39	0.46	0.49	0.52	0.42	0.39
City Roads	32.26	30.66	29.09	28.12	7.79	6.11	4.99	4.55
First-class	11.28	10.83	10.62	10.54	2.71	2.07	1.62	1.38
Second-class	20.98	19.83	18.46	17.58	5.08	4.03	3.37	3.17

Note: Roads density is the ratio of the total area of roads in a certain area (km/km^2). Roads data for Harbin, expressed as a vector line, includes railways, expressways, state roads, and city roads (https://www.amap.com, accessed date 30 March 2021). City roads were merged into two classes in our study. Except for the first-class roads, other classes in the original dataset were merged into the second-class category. The width of railways, expressways, state roads, first-class city roads, and second-class city roads was calculated to be 5 m, 22.5 m, 24.5 m, 30 m, and 16 m, respectively.

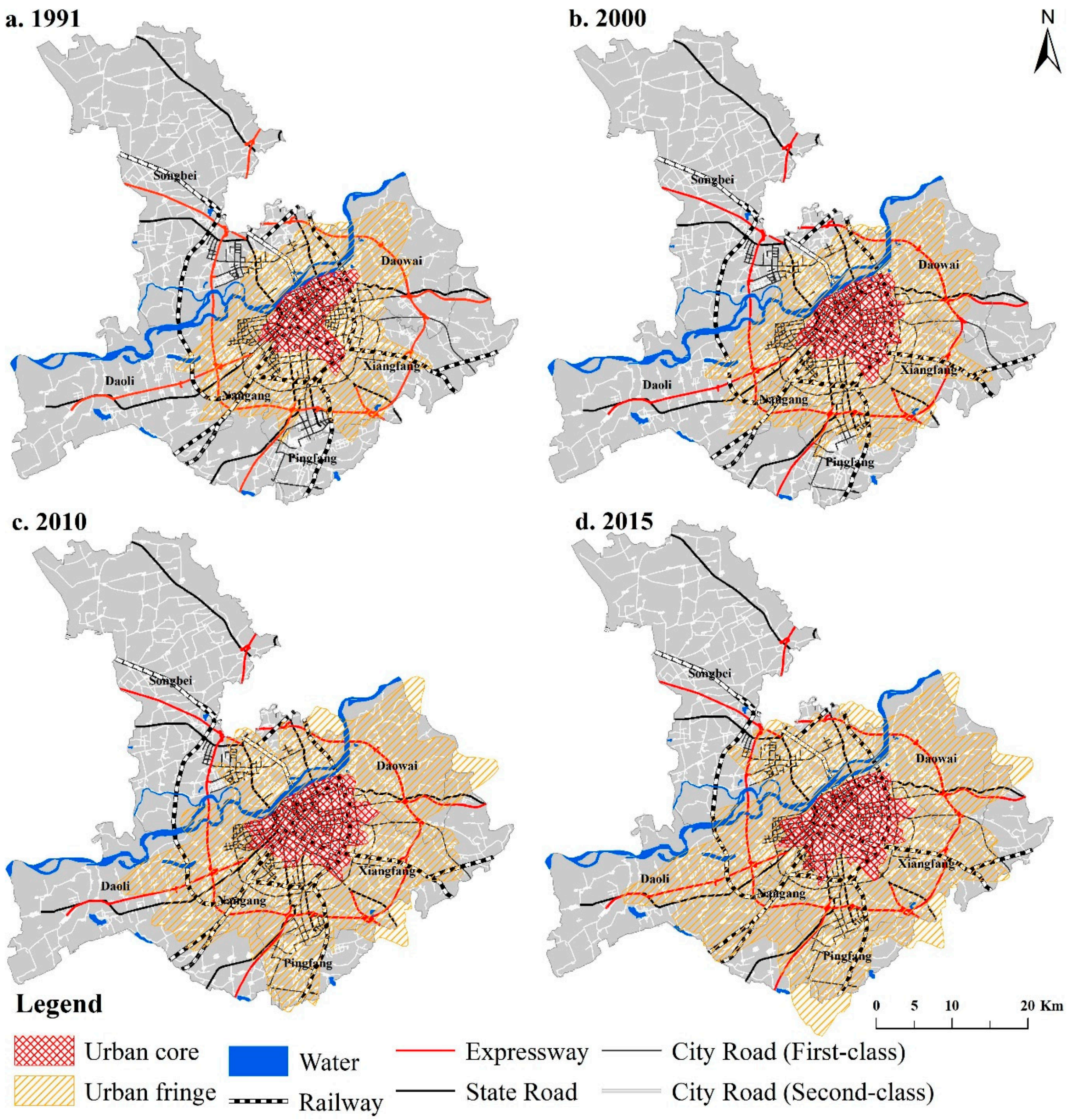

Figure 5. Changes to the Harbin urban fringe in 1991, 2000, 2010, and 2015. The tags in the sub-figures, i.e., (**a**–**d**), are the urban fringe in 1991, 2000, 2010, and 2015, respectively.

3.2. Changes of Urban Expanding Patterns

The ideal outer boundary of the urban fringe, referred to as MFB, expanded during 1991–2015. The supported materials can be found in Supplementary Materials, Figures S1–S4, and Table S1. In 1991 and 2000, the radius between the MFB and the center point were 16.5 km, with a buffer interval of 1.5 km (R^2 values are 0.837 and 0.835, respectively. See Table S1). Meanwhile in 2010 and 2015, the radius between the MFB and the center point were 18 km, with buffer intervals of 1.5 km and 2 km, respectively (R^2 values are 0.783 and 0.797, respectively. See Table S1). These radii were close to the planned inner circle (with radii of 20 km) of the urban system in the Harbin 12th Five-Year Plan. In other words, the Harbin 12th Five-Year Plan had a major influence on Harbin's urban development.

The urban expanding pattern indicates the built-up land pattern in different directions. Figure 6 shows Harbin's expanding patterns varying from 0 degrees to 360 degrees, by overlaying the outer boundary of the urban fringe, the MFB, the difference of distance, and the number of built-up patches. To capture these pattern conversions, we divided the map into different sections based on the dimension degrees. The 0–140 degree points cover Daowai and Songbei Districts, which showed various expanding patterns. The south part of Songbei District distributed between 140 degrees and 190 degrees showed a stable pattern. The areas from 200 degrees to 360 degrees cover Daoli, Nangang, Pingfang, and Xiangfang Districts, which mainly showed a mixed pattern. That is because Harbin West Railway Station, Harbin South Railway Station, Gongbin road, and Hacheng Road contributed to the conversion of surrounding lands into built-up land. Moreover, Harbin development strategies are defined according to urban expanding patterns, which implies these changes.

Changes of urban expanding patterns in different directions and the distribution of built-up land indicate urbanization trajectories, which can be found in Figure 7. The proportion of stable pattern was 5/12 in 1991, 4/12 in 2000, 3/12 in 2010, and 3/12 in 2015. Correspondingly, the proportion of leaping patterns was 17/36 in 1991, 14/36 in 2000, 11/36 in 2010, and 10/36 in 2015. Obviously, stable patterns and leaping patterns decreased during this rapid urbanization period, indicating that built-up land sprawled out. In the 60–180 degrees sections, the built-up land was stable during 1991–2000, and obviously increased during 2000–2010, because the Songhua and Ashi Rivers run through Songbei and Daowai Districts. In the 180–230 degrees section, sprawling and leaping patterns coexisted. The leaping pattern decreased and those with sprawling patterns increased; the main reason for these changes was the increase in built-up land along both sides of the Airport Express to Harbin Taiping Airport. In the 230–330 degrees section, four urban expanding patterns coexisted. The leaping pattern dominated in 1991, and then was gradually replaced by the sprawling pattern. Traffic nodes and routes played a leading role in these changes. Harbin West Railway Station and Harbin South Railway Station both contributed to conversion of surrounding lands into built-up land. South of Harbin, built-up land sprawled under the impact of Hashuang Road, Beijing-Harbin Expressway, and Haping Road. In the 330–60 degrees section, the stable and sprawling patterns converted to mixed patterns between 1991 and 2015. Gongbin Road and Hacheng Road provided conditions well suited to the expansion of built-up land.

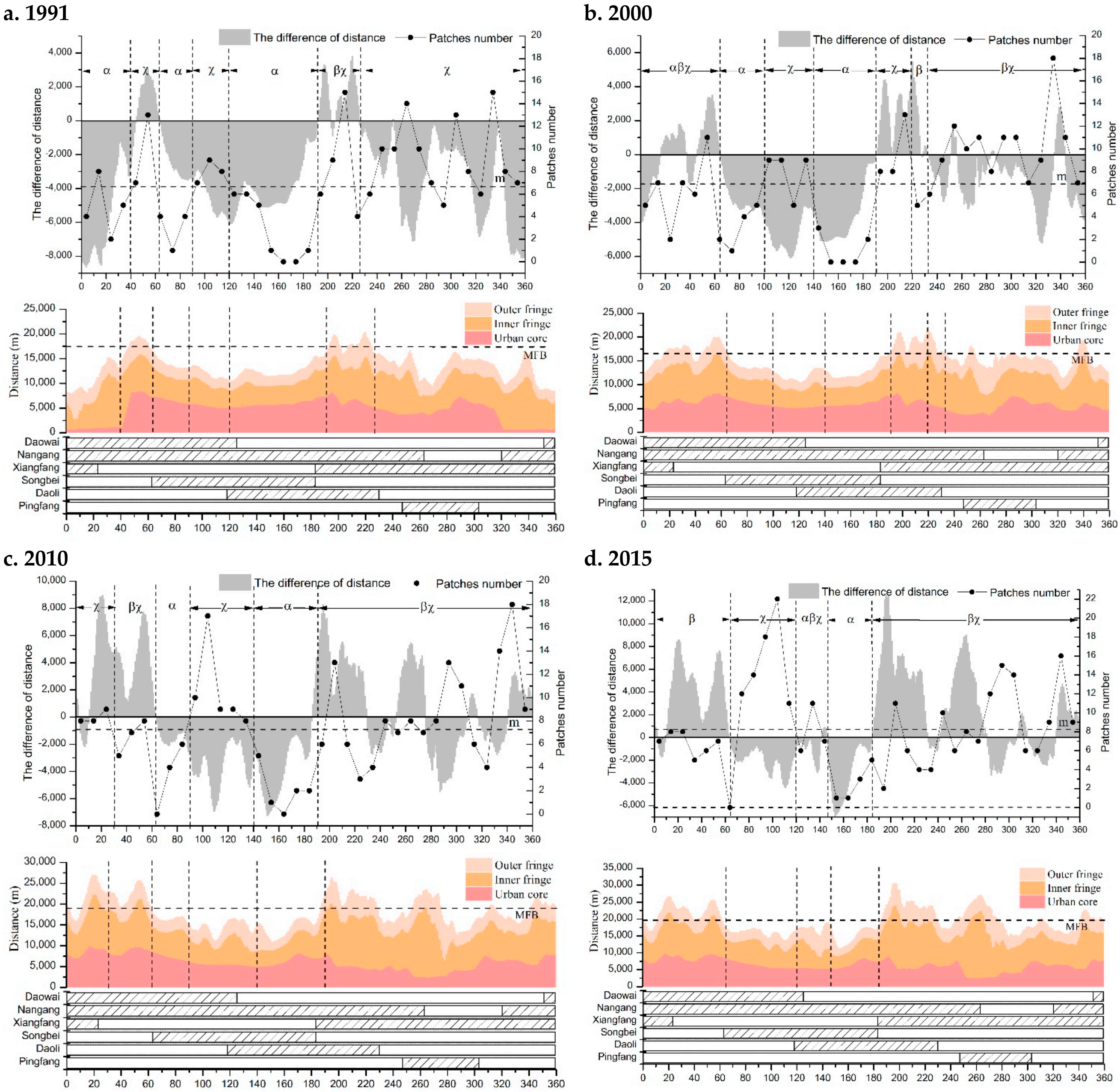

Figure 6. The distribution of urban expanding patterns in the Harbin urban fringe. The tags in the sub-figures, i.e., (**a**–**d**), are the distribution in 1991, 2000, 2010, and 2015, respectively. In each sub-figure, α indicates a stable pattern, β indicates a sprawling pattern, χ indicates a leaping pattern, and βχ indicates a mixed pattern comprised of sprawling and leaping patterns. *m* is the mean number of built-up patches in each direction. MFB is the maximum fragmentation boundary. In each year, the upper sub-figure shows the difference of distance between the MFB and the boundary of the urban fringe in each year. The lower sub-figure shows the distance from each urban zone to the city center point.

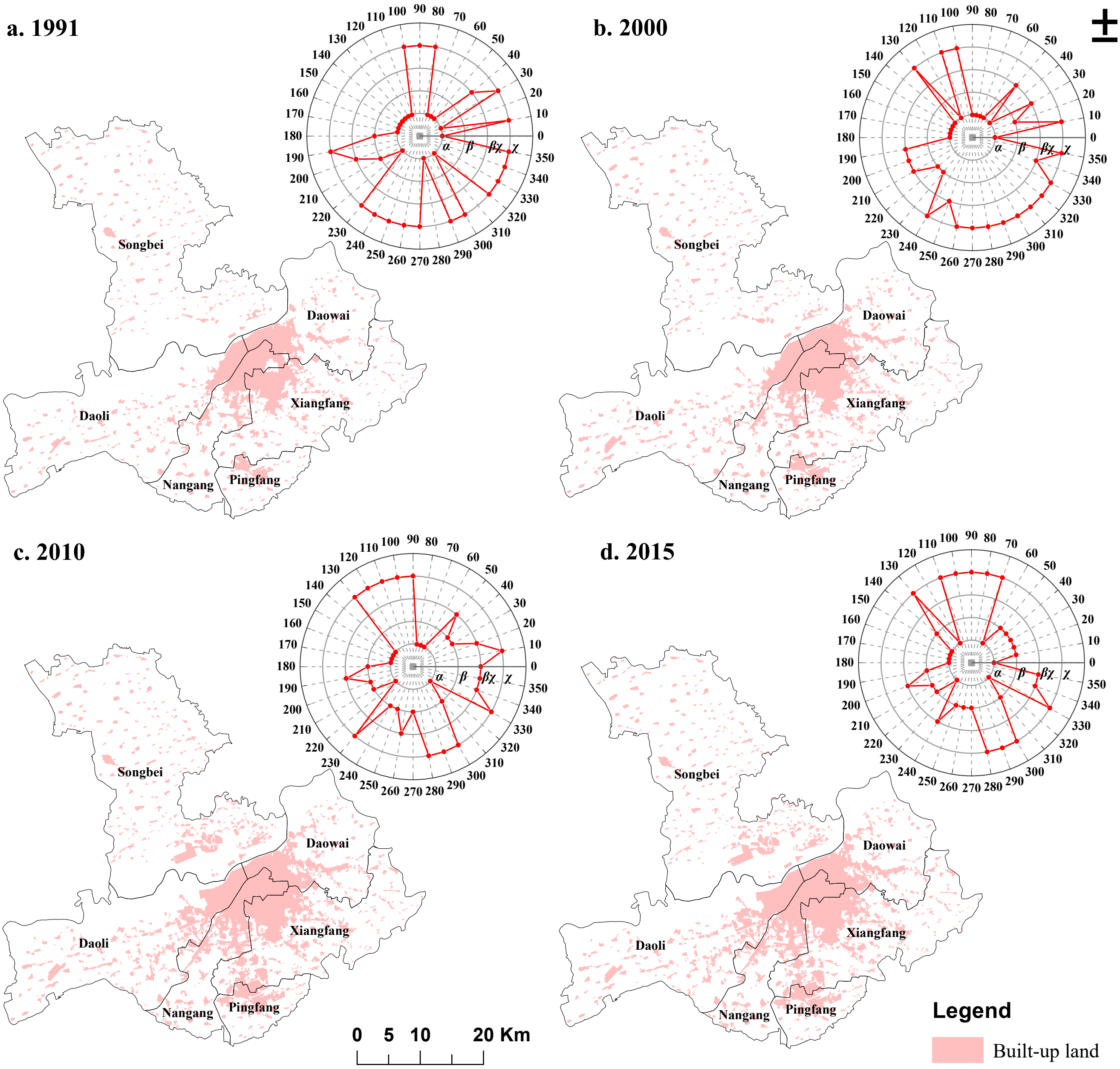

Figure 7. Urban expanding pattern changes in different directions. The tags in the sub-figures, i.e., (**a**–**d**), are the distribution in 1991, 2000, 2010, and 2015, respectively. In the sub-figures, α indicates a stable pattern, β indicates a sprawling pattern, χ indicates a leaping pattern, and βχ indicates a mixed pattern comprised of sprawling and leaping patterns. M is the mean number of built-up patches in each direction.

4. Discussion

4.1. The Model of Detecting Urban Fringe

The aim of detecting the Harbin urban fringe was to guide and regulate the density and intensity of built-up land, which is guided by the Land Spatial Plan and Urban Plan. Furtherly, detecting the urban expanding patterns in the urban fringe helps to protect agricultural land and natural habitat from needing special manage strategies. Our results demonstrate that the Harbin urban fringe can be characterized by ring-patterned expansion. Considering different types of expanding patterns in different directions, governments should adopt different management strategies accordingly.

Harbin, with its mono-centric characteristics, is similar to Shenyang and Changchun, the other two capital cities in Northeastern China, although Shenyang and Changchun generally had higher urban growth rates and became compact earlier than Harbin [64]. Because our model is based on the urban spatial territory of a mono-centric city, it is of great value to growing cities with mono-centric expansion patterns. In contrast to the cities in the Yangtze River Delta [47,65,66], Shijiazhuang and other smaller mono-center capital cities in Northern China are suitable for applying our model to analyze urban expanding trajectories [67]. Although some geometric parameters of built-up land can also be used to describe characteristics of urban expansion, they cannot explain the directionality of urban growth [64,68]. Thus, this model is widely applicable and can reveal characteristics of urban growth, including expanding patterns in different directions and spatial growth extents.

The approach developed in this study has some advantages and disadvantages. First, the SSM uses the vector data of built-up land, which is more convenient for calculating characteristics in different directions than raster data [69]. Thus, the results of the SSM can clearly reflect the directionality of urban development. Second, despite some subjectivity in determining boundary thresholds, boundary determination is very practical for cities with a scattered distribution of built-up land. Meanwhile, we determined land fragmentation based on the number of built-up patches in each buffer ring due to a technique limitation, without considering the size of the built-up land. In further research, it would be beneficial to construct a built-up land fragmentation index system based on the distribution, size, and number of built-up patches. At same time, supervision classification and visual interpretation are less convenient than the methods for impervious surface mapping to obtain built-up land data [70]. Because the SSM is a static research model and the spatial extent of the urban fringe varies with urban growth, research on changes in urban fringe area requires analysis of multiple data periods. Lastly, the urban fringe is a transitional region and thus should be delineated by characteristics of flow elements, such as traffic flow, information flow, and population flow, which are also the spatial linkages between urban and rural areas.

4.2. Expanding Trends and Driving Factors in Urban Fringe

Urban fringe changes in Harbin were closely related to socio-economic growth. During 1991–2000, the urban fringe was in a stable state, with an unchanging spatial range and urban expanding patterns shifting from leaping to mixed patterns. During 2000–2015, the spatial position of the urban fringe moved to the southwest and the spatial range increased rapidly. Meanwhile, the built-up area sprawled gradually and took on a more irregular shape.

Urban expanding patterns in Harbin were largely affected by the space policy and development plan. The development plan aim to optimize urban resource allocation, including land use, industrial space, and transportation and other infrastructure construction. Therefore, Harbin has formed a "two-axis, four-ring, and ten-radial" traffic network. Such traffic facilities offer great convenience for constructing economic zones, especially the Haxi New Zone, Qunli New Zone, Xuefu Young Town, Songbei New Town, Songpu Industrial Zone, Hannan Industrial New Town, and Hadong Industrial Zone. Meanwhile, functionality in each zone has been improved. Industry lies mainly in southern areas, farming in northern areas, and business and administration in western and eastern areas. These spatial patterns in Harbin will exist well into the future and continue to be optimized.

The characteristics of Harbin's spatial territory vary from the urban core to the urban fringe. The roads densities in the urban core are higher than in the urban fringe, which appears in many cities worldwide [71,72]. Unlike the sub-urbanization trends in many cities in developed countries, such as population density on built-up land in peri-urban area only being half the density of urban areas in Europe [5], the Chinese government has implemented several policies for urban development. For example, land acquisition in urban fringe areas, the metropolitan development plan, and investment guidance provide conditions for settling populations in each spatial zone [72,73]. Thus, the urban core has gathered a large amount of real estate investment in China during 1991–2015 [72,74]. Due to the real estate boom in China during this period [74], our results show that roads density and built-up land density in the urban core are far beyond the urban fringe. Similar to Detroit, Leipzig, and other shrinking cities, as well as other cities in Northeastern China, Harbin is facing a more and more serious population decline, which has a huge impact on its urbanization process and patterns [23,75,76]. Therefore, promoting "inventory planning" instead of "incremental planning which needs effective land-use and suitable urban growth strategies in Harbin, as well as in other shrinking cities in China at present, plays an important role in alleviating urban shrinkage for future development [77,78].

5. Conclusions

This study has developed a novel model, the Spatial Segmentation Model (SSM), to detect the urban fringe that was applied in Harbin city. We found that spatial territory changes were highly relative to transport infrastructures in Harbin. Meanwhile, the roads density in the urban core was higher than in the urban fringe. Especially for city roads, the roads density in the urban core was more than 4 times greater than in the urban fringe. Furthermore, urban expanding patterns were calculated based on the outer boundary of the urban fringe, the MFB, the difference of distance, and the number of built-up patches, which indicates the built-up land pattern in different directions. We found that the growth of the urban fringe is closely related to the development of social economies, as well as the space policies and development plans designed by governments. Because the relationship between the growth of the urban fringe and the development of social economies in Harbin is mainly summarized from qualitative understandings, further research in any regions of the world would be welcomed. Similar to post-industrial cities such as Detroit, Leipzig, and other shrinking cities, Harbin should take action to reduce population declines. Effective land-use and suitable urban growth strategies play an important role in alleviating urban shrinkage. Thus, understanding the dynamics, urban expanding patterns, and driving factors in the urban fringe can help us form a basis for future urban development.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/land10080876/s1, Figure S1: The distribution of the number of patches in 1991 with different buffer intervals, Figure S2: The distribution of the number of patches in 2000 with different buffer intervals, Figure S3: The distribution of the number of patches in 2010 with different buffer intervals, Figure S4: The distribution of the number of patches in 2015 with different buffer intervals, Table S1: The fitting function and R^2 summary.

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